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## **SURFACE FEATURES OF THE CIRCULATION IN FJORDS OF SOUTHERN CHILE OBSERVED IN ERS AND LANDSAT IMAGES**

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### **ABSTRACT**

Surface features of the hydrodynamics at the mouth of Aysen Fjord, in the Chilean Inland Sea, were described using Landsat and ERS-SAR images in combination with field data. A set of seventeen radar images from ERS, along with one Landsat (ETM) were analyzed to study the surface features observed in this region, where fresh water input is an important contributor to the dynamics of the estuarine system. Field data were provided by current measurements obtained with an Acoustic Doppler Current Profiler (ADCP) mounted in a catamaran looking downward, which was towed from a boat during two semidiurnal cycles to obtain repetitions over two transverse transects. There were also density measurements obtained from CTD (Conductivity, Temperature and Depth) vertical profiles in the water column and from a surface termosalinograph (Conductivity, Temperature) mounted onboard of a research vessel. The results of this campaign in Aysen Fjord were associated to the surface features observed in satellite images.

The results show the main features of the circulation at the mouth of this fjord and other phenomena of interest for physical oceanography. Noteworthy is a frontal structure suggested on both types of images. This feature is partially supported by ADCP measurements and strongly suggested by density measurements. Packages of internal waves in Costa Channel are also suggested in radar images, while the distribution of the fresh water plume is supported by the Landsat image. Satellite images provided valuable guidance to focus the research in a selected area and phenomena.

## INTRODUCTION

Making use of one ERS satellite image from Aysen Fjord, southern Chile, [Caceres et al. \(2002\)](#) described the main characteristics of this system, and suggested evidence of a convergence region and internal waves at its mouth. The position and orientation of this convergence region suggested a tendency of the flow to go to the south, coming into Costa Channel. Theoretically, this would be a typical response for an across-fjord geostrophically balanced flow ([Dyer, 1997](#)), where Coriolis accelerations are balanced by the transverse pressure gradient. In that study, [Caceres et al. \(2002\)](#) studied the transverse variability of Aysen Fjord, between Colorada Island and the connection to Pilcomayo Channel, approximately 6 km from the mouth in the up-fjord direction, making use of field current measurements, to assess the influence of the wind effect and submarine topography in the transverse dynamics during a semidiurnal tidal cycle. They observed that the dynamic balance switches from geostrophic conditions under calm or low wind intensity, to ageostrophic under moderated to strong winds. In these systems, geostrophy in the transverse dimension is suggested by the unequal depth of the layers of flow in the across-fjord dimension, which will be higher on the left side of the direction of the flow, according to Margules relation ([Prandtl, 1952](#)). Therefore, under geostrophic conditions we should expect that the surface fresh water layer going down-fjord be higher on the southern side (left side of flow direction) of an east-west oriented fjord.

Nevertheless, the work of [Caceres et al. \(2002\)](#) had no field evidence to explain the features observed in the ERS image at the mouth region, approximately 3 km to the southwest of Colorada Island. The present work provides insights on the processes occurring at the mouth region, in describing both the subtidal velocity distribution of the flow and density field to the south of Colorada Island, and in correlating them to the surface features observed in ERS and Landsat satellite images.

## METHODS

### Field measurements

Current measurements were made with an Acoustic Doppler Current Profiler (ADCP) to study the transverse variability of the flow at the mouth of Aysen Fjord ([figure 1](#)). Measurements were made on November 17 and 18, 2001, with an RD Instruments WH of 307.2 kHz looking downward mounted in a catamaran of 3 m length, which was towed from the side of the fishing boat "Millabu" to a maximum velocity of 5 knots. 21 repetitions of the transects 1 and 2 shown in [figure 1](#) were made with the ADCP during 24.5 hours. Vertical bin size of the velocity profiles was 4 m and ensembles were made every 30 minutes. The first bins size was centered at 6.24 m depth, so the surface layer over this depth was not resolved by the measurements. Maximum depth of the velocity measurements was about 120 m over maximum range of 200 m, so restricting the measurements to areas shallower than 200 m.

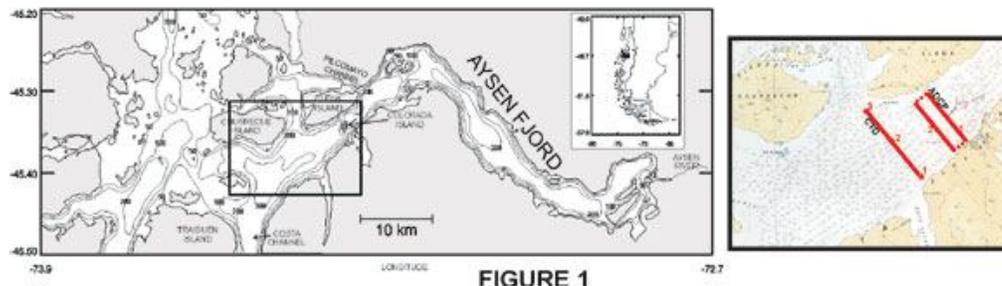


Figure 1. Main study area and position of ADCP transects and CTD stations

Navigation data was obtained with a GPS (Global Positioning System) ASHTEC Z-12 interfaced to a laptop computer in combination with the ADCP measurements. Repetitions of transect 1 were made over a submarine bank, a feature that seemed to be the submarine extension of Colorada Island, which is absent on transect 2.

Compass data of ADCP was corrected following the method explained by [Joyce \(1989\)](#) and bad velocity data was removed following the procedure of [Valle-Levinson and Atkinson \(1999\)](#). The semidiurnal tidal signal, represented by the  $M_2$  constituent with a period of 12.42 hours, and the diurnal tidal signal, represented by the  $K_1$  constituent with a period of 23.93 hours, were separated from the subtidal signal of the flow components observed using least square sinusoidal regression analysis ([see Lwiza et al.,](#)

1991). The subtidal signal represented the mean of the observation period and the fit of the least square analysis explained over the 85% of the data variation during the sampling period. For the purposes of this work, subtidal flow may also be understood as representative of the mean flow during the sampling. A coordinate system was adopted where the velocity components along-fjord and across-fjord were  $u$  and  $v$ , respectively. Velocity data was rotated counterclockwise to a direction of the highest variability and intensity of the tidal currents along-fjord and to the weakest tidal flows across-fjord.

Along with the current sampling, density measurements of seawater consisting of repeated vertical profiles using a CTD (Conductivity, Temperature and Depth) Sea-Bird 25 at the stations 1,2 and 3 indicated in figure 1, were made from the research vessel AGOR "Vidal Gormaz". A total of 13 profiles for each station were made during the sampling period. Continuous sea surface density measurements from the termosalinograph mounted onboard were also taken during this period.

### Remote sensing observations

A set of seventeen SAR-ERS satellite images of the mouth region were analyzed in searching for the phenomena occurring at the mouth of Aysen Fjord. As radar images were from ascending and descending orbits, they were rotated and transposed, where appropriated, to an earth coordinate system orientation. Speckle effect was reduced using Frost filter and images georeferenced using field control points. The image of February 3, 1993, where the features of interest appeared more evident, was selected to the analysis of the present study (figure 2).

A Landsat 7 ETM satellite image obtained on March 11, 2001 (figure 3), was also used to provide information in the visible and infrared region of the electromagnetic spectra. Band combination of the Landsat ETM image was 7:4:1. An interactive stretching was applied to the three bands to enhance the contrast in the blue band to better observe the surface patterns suggested by the surface fresh water input.

Digital process of both radar and Landsat images was made using ENVI 4.0, a software developed by Research Systems Inc.

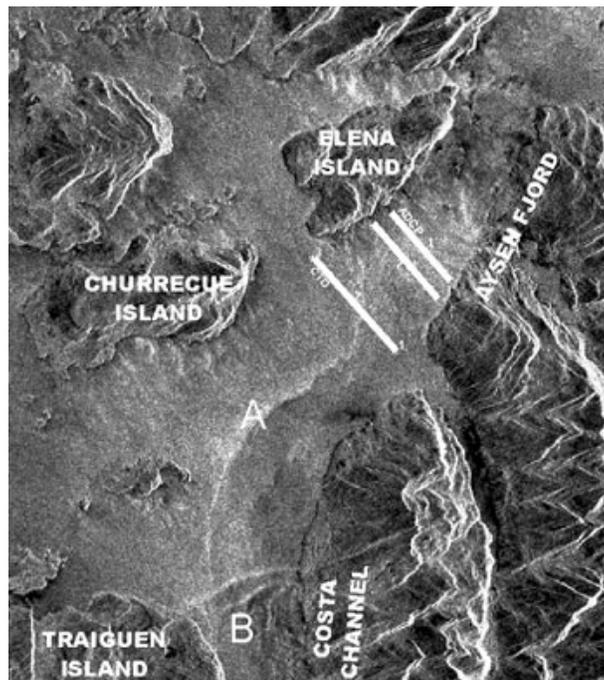


Figure 2. ERS-1 SAR image of February 3, 1993. A convergence region (A) at the mouth of Aysen Fjord and a package of internal waves (B) are suggested from the picture.



Figure 3. Landsat 7 ETM satellite image obtained on March 11, 2001. An estuarine plume going to Costa Channel is suggested from the filtered image.

### River discharge data

River discharge data for the time of Landsat image and ADCP sampling were available for Aysen river, located at the head of Aysen Fjord ([figure 1](#)). On March 11, 2001, it was about  $1800 \text{ m}^3/\text{s}$ , during the Landsat image acquisition, matching the starting of decay of the largest rainy event of that year (maximum of  $3240 \text{ m}^3/\text{s}$  on March 10). In contrast, on November 18, 2001, during the ADCP sampling, river discharge was  $395 \text{ m}^3/\text{s}$ , below the annual mean of  $567 \text{ m}^3/\text{s}$  for the year 2001. No river discharge data was available for the time of the ERS image.

## RESULTS

The motivation for this study was to explore the mechanisms underlying the features observed at the mouth region of Aysen Fjord, using a combination of field current measurements and density observations, along with remote sensing observations.

[Figure 2](#) shows the selected ERS satellite image representative of the features under scrutiny. There is a convergence zone suggested by the white line running from the south of Elena Island to the west entrance of Costa Channel, indicated by "A". This feature might be attributed to the combined effect of the fresh water surface layer going down-fjord, which turns left at the mouth to come into Costa Channel, and to the effect of tidal forcing coming from the east.

In agreement with this tendency, [figure 3](#) shows the Landsat image where there is also evidence for a south turning into Costa Channel suggested by the fresh water plume of lighter blue (letter A). Light blue tones of this plume strongly resemble the pattern suggested by the white line in radar image (letter A in [figure 2](#)). [Figure 3](#) also shows a tendency at the head of the plume into Costa Channel to reach first the left side of flow direction, suggesting Coriolis effect (letter B).

The results of the current measurements in transect 2 are presented in [Figure 4](#). The subtidal (or mean) flow reveals a three layer structure, where there is a first outflow surface layer (gray tones) of ca. 15 m depth attributed to the effect of fresh water buoyant input coming from the head. A second layer of inflow (white) between 15 and 70 m depth attributed to the effect of tidal forcing, and a third deep layer (gray tones) below 70 m probably produced by a longitudinal pressure gradient set up by the wind in the up-fjord direction. There are unequal depths of the flow layers in the across-fjord dimension, as they are deeper on the left side of the flow direction than in the right side, suggesting the effect of Coriolis accelerations in pushing the flow to the left side. This figure also shows how the first thin layer is absent into the first 300 m of distance from the northern side, suggesting horizontal shears that might lead to the formation of convergence or turbulence regions.

The evolution in time of the surface salinity during the sampling period is plotted in [figure 5](#). Numbers on left side represent the CTD station number of [figure 1](#). Spatial displacements of a strong surface gradient of salinity in the across-fjord direction are observed, suggesting tidal effect in lateral movements of a convergence region.

The mean salinity contours of the sampling period in a section across-fjord are shown in [figure 6](#). Numbers on top represent the CTD station number of [figure 1](#). Waters of low density are observed at surface on the southern side, in consistency with flow measurements of the surface layer shown in [figure 4](#).

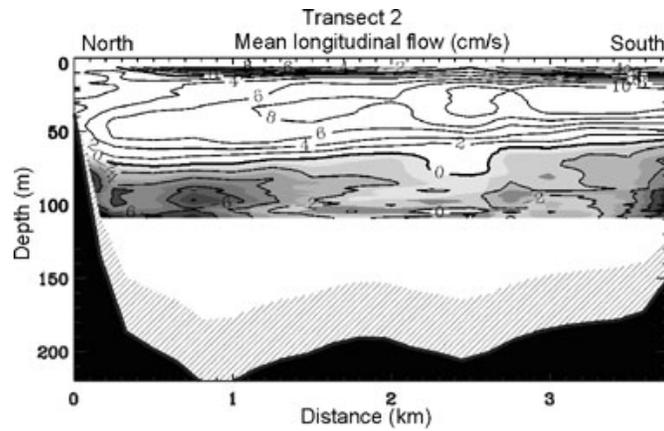


Figure 4. Longitudinal mean flow derived from ADCP measurements at transect 2. A three layer structure is evident from the figure (looking up-fjord).

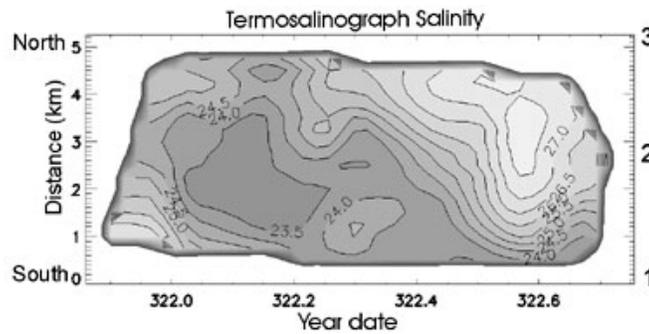


Figure 5. Surface salinity distribution and its evolution in time obtained from termosalinograph records.

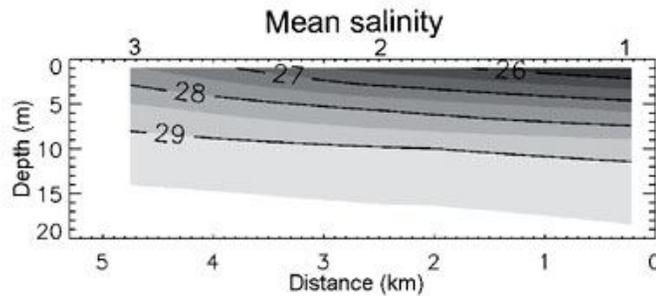


Figure 6. Mean salinity contours of the surface layer (first 20 m) obtained from CTD stations (looking up-fjord). Low salinities dominate on the southern side.

## DISCUSSION

A fully understanding of the dynamics in the region of the convergence observed in SAR images could not be provided by the current measurements of ADCP, as the maximum range of the instrument restricted the description of the mean flow to the south of Elena Island region. Nevertheless, the field current measurements provided valuable first evidence suggesting the presence of this convergence. Low river discharge during this experiment may also have contributed to relax the velocity gradients and to weak the patterns under examination. More consistent findings about the convergence were provided by the density measurements, where the evolution in time of its position was evident from [figure 5](#). Another support for evidence of this convergence is provided by the work of [Silva et al. \(1997\)](#), where the vertical contours of salinity made during a field campaign of CTD casts also suggest the position of the plume in the same region observed in the ERS image.

As the convergence region was not observed in the whole set of ERS images, it seems to be a transient phenomenon triggered by a combination of forcing effects. Further investigations including long-term current measurements are also needed at the deep region of the mouth to understand the temporal variability and dynamics of this convergence.

The tendency of the surface flow to go into Costa Channel, suggested by ERS and Landsat TM images, and the shape of the head of the plume into this channel observed in Landsat image, both suggest influence of Coriolis effect and transverse geostrophic dynamic balance. This was supported by the current measurements, as they showed slopes of the zero velocity contour in the transverse dimension in agreement with geostrophy.

In addition to the convergence observed in [figure 2](#), there was also a package of internal waves suggested in the ERS image, indicated by "B", where no field measurements are available for a thorough discussion of this feature. Theoretical approximations suggest that they might be produced by a combination of a highly stratified buoyant surface layer flowing in a region of constricted coastline. As the bottom profile along Costa Channel gently moves around 200 m, bottom effect does not appear to be relevant in producing these internal waves. Long term measurements of moored instruments at the northern entrance of Costa Channel would be necessary to provide insights about the processes underlying this feature.

In summary, satellite images provided valuable guidance to focus the research in selected areas and phenomena. They were useful tools to provide insights about the phenomena under study, as they covered a broad area involving the full spatial extension of them.

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