Oceanography of Nootka Sound

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1 Introduction

This paper is a *work in progress*. It's goal is to summarize some of the available oceanographic literature on Nootka Sound. After synopses are prepared, it will be easier to write something more definitive. Since a synopsis "borrows" the knowledge of other authors we should acknowledge those authors, but initially accept all textual errors as our own (transcription), until such time that we can examine the nature and location of the error.

Papers included in this synopsis:

Reference	**Topic**	**Cite**	**Page**
Knox, 2015	CO_2 fluxes	[1]	3
Koehlinger, 2015	Water masses	[2]	7
Daniels, 2015	Salinity Imbalance	[3]	12

2 [1]: Are fjords sources or sinks of CO_2?

2.1 Abstract

- atmospheric CO_2 has increased $\approx 40\%$ in the past 200 years; anthropogenic activities
- $\approx 1/2$ of the CO_2 is anthropogenic in the atmosphere, the other 1/2 is taken up in near equal proportions by the terrestrial biosphere and the ocean
- By 2000 the open ocean drew down $2 \pm 1\,\mathrm{Pg\,C\,yr^{-1}}$
  - uptake in subtropics and middle latitudes
  - release in tropics and polar latitutes
- global CO_2 cycle has been altered
- Uptake in Nootka Sound is about the same at 50° North latitude in the Pacific
- Study examines CO_2 fluxes in Nootka Sound
- mean $\Delta\,\mathrm{p\,CO_2}$ = -126.9 μatm, mean influx = 3.2 $\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$
- annual: 1.2 $\mathrm{mol\,C\,m^{-2}\,yr^{-1}}$ = 14 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$

2.2 Introduction

- coastal systems – disproportionate high ratio of carbon and nutrients when compared to atmosphere; large terrestrial inputs
- coastal systems account for 10-15% of ocean surface; sequester 40% of oceanic carbon
- main export of organics to deep sea
- Nootka Sound – decreased daylight hours; strong weather systems; lower salinity (large river water flux from precipitation)

- study wants to determine if inlets in Nootka Sound are sinks or sources of CO_2
- Need to measure atmospheric and oceanic CO_2
- compute flux using the wind speed and the Schmidt number (≈ viscosity, salinity and termperature)
- hypothesis: In Nootka Sound, **uptake** of CO_2 is predicted to be related to: wind speed, lower temperature, lower salinity
- decreasing uptake with distance from fresh water source (fresh water is colder and less saline)
- head of inlets: colder, less saline
- Want to determine if biological community contributes to CO_2 flux. This will require O_2 measurements.

2.3 Study Site

- Sampling dates: 13–17 December 2014
- Muchalat Inlet (MI): 55 km long, 75m sill at mouth (Williamson Sill), average depth = 220m; 33 stations
- Tahsis Inlet (TI): 38 km long, 85 m sill at Tssowwin, average depth = 135m; 22 stations

2.4 Results

- Salinity and Temperature
  - surface water of MI fresher than TI; discharge of Gold River
  - temperature and salinity decrease with increased distance from mouth
  - MI: mean temperature: 7.97 °; salinity 0.52 – 8.72 PSU, mean=4.17
  - TI: mean temperature: 6.69 °; salinity 7.8 – 21.5 PSU, mean=14.49

- Dissolved inorganic carbon (DIC)
  - MI: min 239 μ mol kg^{-1}, max=615, mean=382
  - TI: min 467 μ mol kg^{-1}, max=1406, mean=947
  - MI: no spatial pattern in DIC
  - TI: there is a 2 fold increase moving North to South
- Alkalinity
  - MI: min 206 μ eq kg^{-1}, max=623, mean=395
  - TI: min 507 μ eq kg^{-1}, max=1144, mean=993
  - increases moving away from the river mouths
- Dissolved Oxygen
  - MI: mean 62.2%
  - TI: mean 57.6%
- $\Delta\,\mathrm{p\,CO_2}$
  - atmospheric CO_2 comes from Environment Canada
  - $\Delta\,\mathrm{p\,CO_2}$ (sw-atm) – difference between the calculated oceanic pCO_2 and measured atmospheric pCO_2
  - $+\Delta\,\mathrm{p\,CO_2}$ (sw > atm) represents sourcing of CO_2 from seawater, $-\Delta\,\mathrm{p\,CO_2}$ (sw < atm) represents sinking of CO_2 to seawater
  - MI: acts as a sink and a source; lower saline waters act as a sink
  - TI: Overall sink of CO_2
  - MI: mean 84.5 μatm pCO_2
  - TI: mean -169.3 μatm pCO_2
  - Flux MI: -4.7 mmol C m^{-2} d^{-1} of CO_2
  - Flux TI: -1.7 mmol C m^{-2} d^{-1} of CO_2

2.5 Discussion

- Tahsis Inlet drains a larger area, via Hecate Channel. This supplies higher soils and terrestrials. This may explain the higher DIC.
- DIC and alkalinity are dominant variables in calculation of pCO_2
- pCO_2: Tahsis Inlet has a 2 fold greater $\Delta\,\mathrm{p\,CO_2}$, yet the mean flux is only 1/3 of Muchalat Inlet's flux
- MI has higher wind speeds
- Nootka Sound **absorbs** 294.4 $\mathrm{mmol\,C\,m^{-2}}$ every winter. Assuming these winter rates carbon uptake is in the area of 1.2 $\mathrm{mol\,C\,m^{-2}\,yr^{-1}}$ or 14 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$.
- Biological communities contribute to the CO_2 flux
  - Theory: water should be supersaturated with O_2 while acting as a sink for atmospheric CO_2 due to primary production.
  - as freshwater moves away from rivers it slowly mixes with more saline water driven by the wind — induces vertical mixing.
  - all 3 inlets are undersaturated for oxygen
  - all 3 inlets **sink** atmospheric CO_2
  - therefore; primary production does not drive CO_2 in the winter in Nootka Sound
  - $\Delta\,\mathrm{p\,CO_2}$ is an indicator of air–sea CO_2 exchange, signifying a gradient for CO_2 to move across boundary. Low rates of primary production characterize the ecosystem due to insufficient solar radiation.

3 [2]: A Description of Water Masses in Nootka Sound and Estimation of Diffusivity (κ) and Upward Velocity (w) · · ·

3.1 Abstract

- Looking at the water property data from Nootka Entrance Sill, Nootka Basin, and the three inlets (Tahsis, Muchalet, Tlupana)
- measurements of salinity, temperature, and dissolved oxygen were used to characterize water masses
- temperature advection, diffusivity: Range of κ: 2.8×10^{-5} to $4.5 \times 10^{-5}\,\mathrm{m^2\,s^{-1}}$
- localized downwelling: Range of w: -5.4×10^{-6} to $-2.0 \times 10^{-5}\,\mathrm{m\,s^{-1}}$

3.2 Introduction

- Inlets: Muchalat, Tahsis, Tlupana. Rivers: Gold (Muchalat); Tahsis, Tsowwin (Tahsis); Sucwoa, Conuma (Tlupana)
- Estuarine circulation
  - saline water enters inlets at depth from the open ocean (Nootka Entrance Sill) and upwells and mixes with freshwater supplied by the river system
  - mixed water exits the inlet near the surface
- this type of circulation is one of the determinants of dissolved O_2 levels below the photic zone (primary production, O_2 production)
- need deep water renewal $\Rightarrow$ decreasing levels of dissolved O_2 resulting in hypoxia
  - oxygen minima affect composition and distribution of the species in the water column (bacteria, archaea, zooplankton, fish)
- sills restrict renewal water masses from entering the estuary

- Nootka Entrance Sill: cold, saline water ⇒ quite dense: sinks and renews the deeper water
- Secondary Sills: Tahsis Narrows (?), Williamson Sill (Muchalet)
- we are going to require two renewal events. We expect the deep water inside the sills to have different characteristics compaired to water at the entrance sill
- stratification of water column impacts circulation and mixing
- Nootka Sound
  - highly stratified estuary
  - relatively shallow mixed layer
  - remainder of water column is stably stratified ⇒ inhibiting mixing of deep water
  - past research: Tully, 1937 - tidal mixing in July; Pichard, 1963 - TS characteristics around sills in May, June, July
  - Description of water masses

3.3 Study Site

- December 11-21, 2015
- 36 stations: Nn in Nootka Basin, Mn in Muchalet Inlet, and Tn in Tahsis Inlet.
- study will characterize and describe water masses in Nootka Sound using T, S, O_2
- these parameters allow computation of diffusivity and localized downwelling

3.4 Results

- Nootka Entrance Sill:
  - temperature: $10.7 - 10.9\,^{\circ}C$
  - salinity: 29.8-31.1 PSU
  - oxygen saturation: 89.8-93.2%
- Muchalat Inlet:
  - temperature: $7.5 - 14\,^{\circ}C$
  - salinity: 28-33 PSU
  - oxygen saturation: 0-91.2%
- Tahsis Inlet:
  - temperature: $8.5 - 12.5\,^{\circ}C$
  - salinity: 27.5-32.5 PSU
  - oxygen saturation: 5.8-89.3%
- Mulchalat Inlet: Look at Figure 3 in original paper: Wedge of warmer water at approximately 50m along the main axis of the inlet. Expanding upward.
- Tahsis Inlet: Look at Figure 5 in original paper: Moving from station N2 to T1. There are 2 pockets of warm water: (N7), and (T4,T3,T2,T1). Look at the isohalines in (T23,T24) and T7.

3.5 Discussion

- TS plots show distinct water masses in each inlet
- Mulchalet: coldest, most saline, least O_2 at depths below about 125m
- This mass is below Nootka Entrance Sill (50m) and Williamson Sill (75m).
  - $\Rightarrow$ low O_2 indicates water is present for some time

- 2nd water mass - extending through water column at mid salinities and hi temperature
- 3rd water mass - "fresher" water, higher O_2, cooler temperature; likely entering inlet recently

- Tahsis Inlet:
  - Tsowwin Narrows - warmer, better oxygenated water (influx of new water mass from Tsowwin River)
  - colder and less oxygenated water mass found on other side of Tsowwin Narrows Sill (sill depth 85m)

- Interesting Feature: Warm water wedges near surface:
  - Mulchalet: temperature: $12.5 - 14\,^{\circ}C$; 20-50m
  - Tahsis: temperature max : $13\,^{\circ}C$; Tsowwin River outflow influences TS in mid region of inlet
  - For all three inlets the base of temperature wedge is about 50m. Depth of Nootka Sound Sill is 50m. Warmer water enters sound over the sill is more likely to remain at shallow water mass, depending on salinity profile, $\Rightarrow$ temperature wedge is a remnant of an **earlier** mass of water flowing over the sill.

- Water characteristics:
  - Water over the sill at station N2 is well mixed and has a uniform temperature.
  - Value of w shows there is some amount of downwelling or downward wind forced flow is operaturing
  - w decreases towards the mouth of the Mulchalet Inlet
  - using calculated w, a 50m depth is reached betwwen 29-52 days.
  - require more empirical information

Station	**Depth (m)**	$\kappa\,(\mathrm{m^2\,s^{-1}})$	$w\,(\mathrm{m\,s^{-1}})$
M4	32-41	4.5×10^{-5}	-1.4×10^{-5}
M9	36-45	2.8×10^{-5}	-2.0×10^{-5}
M11	39-48	3.5×10^{-5}	-1.2×10^{-5}
M15	42-51	3.3×10^{-5}	-5.4×10^{-6}

Table 1: Water characteristics in Mulchalet Inlet.

3.6 Conclusions

- Nootka Sound and its inlets have stagnant deepwater lay: $\Rightarrow$ uniform TS qualities, and low O_2
- Only found small scale physical processes at work mixing in this fjord, we are seeing little effect for κ (diffusibility), and w (vertical velocity)
  - κ: 2.8×10^{-5} to $4.5 \times 10^{-5}\,\mathrm{m^2\,s^{-1}}$
  - w: -5.4×10^{6} to $-2.0 \times 10^{6}\,\mathrm{m\,s^{-1}}$
- Nootka Sound: highly stratified estuary, salinity changes rapidly in the top 5m

4 [3]: Effects of cross channel salinity imbalance due to freshwater influence in a narrow estuary.

4.1 Abstract

- Knox is looking for insights into questions of cross channel density structure effects on circulation in a narrow basin
- what is the contribution of high freshwater input and its effect on transverse density structure

4.2 Introduction

- past research: in estuaries research focuses on the longitudinal and vertical processes
  - along channel transport of salt and nutrients
  - Figure 1 on Page 17 (after [1]) shows typical estuarine circulation in a BC fjord.
- We tend to ignore the lateral dynamics. Underlaying phenomenon:
  - geostrophic currents
  - thermal windows
  - product of cross channel balance of horizontal pressure gradient
  - Coriolis effect
- Nootka Sound
  - like most fjord systems
    - small river discharge compared to total fjord volume
    - substantial stratification, confined to near surface
  - significantly large freshwater input, window rains allow basin to adjust to a state of *geostrophic equilibrium*

    * geostrophic currents become a potential component of overall water column velocity
    * ASIDE: So in an inlet like Tahsis Inlet, saline inflow is along east side of inlet, brackish outflow is along west side of inlet
    * This situation is shown in Figure 2 on Page 18 illustrating estuarine circulation in Tahsis Inlet.

- Cameron, 1951: BC fjords are narrow, some complications are suppressed due to long, narrow, deep fjords with plunging sidewalls

- River discharges:

  - Gold River: December 1998 mean=133,840 $\mathrm{L\,s^{-1}}$, annual mean=83000 $\mathrm{L\,s^{-1}}$
  - Tahsis River: December 1998 mean=15305 $\mathrm{L\,s^{-1}}$, annual mean=8348 $\mathrm{L\,s^{-1}}$
  - study demonstrates that lateral basin dynamics will reflect density imbalance condition with inflow of more saline waters on east, and outflow of fresher waters on west.

- Positive Result: Establishes importance of considering cross-channel components when deliberating contribution of current in narrow estuarine channels with high freshwater flux.

  - longitudinal currents in narrow inlets are NOT driven exclusively by along-channel density gradient
  - transverse gradient and forcing from earths rotation may play important role in narrow estuarine circulation

4.3 Methods

- Look at density structure by collecting T, S, and pressure

- Tahsis Inlet: Station Tu1 (near Leiner River) to Tu6 (near Tsowwin River), max depth 200m

- Muchalat Inlet: Station Mu1 (near Gold River) to Mu3 (well inside inlet), max depth 320m

- Some metrics: v(y) - longitudinal fjord velocity, u(x) - cross fjord velocity, CTD - instrument for measuring seawater characteristics, Geostrophic Current, σ_{T} - seawater density

4.4 Results

- density primarily controlled by salinity in fjord-like estuaries
- Tahsis Inlet: calculated v(y) (longitudinal fjord velocity) in the north of the inlet to Tahsis Narrows suggests a 2-layer estuarine circulation
  - Top Layer: fresher outflow on the west side of the inlet, a result of rotational forcing
  - Mid Layer: saline inflow forced to east side of inlet
  - refer to Table 2 on page 14.
- at station TU_5, there is a 3-layer system, with two outflow layers one between 0 and 20m, and a second layer below 55m. No explanation is provided for 3-layer circulation.

Flow	TU_1	TU_2	TU_3	TU_4	TU_5
Inflow	0.1877_{0m}	0.1231_{deeper}	0.0746_{0m}	$0.5864_{<20m}$	0.0920_{20-55m}
Outflow	-0.1840_{45m}	$-0.2118_{<45m}$	-0.0534_{deeper}	$-0.1088_{>20m}$	-0.2392_{0-20m}
Outflow	-	-	-	-	$0.0053_{>55m}$
Layers	2	2	2	2	3

Table 2: Inflow and Outflow velocities measured in Tahsis Inlet (all velocities are in $\mathrm{m\,s^{-1}}$, for stations TU_1 – TU_5).

5 Conclusion

Appendix

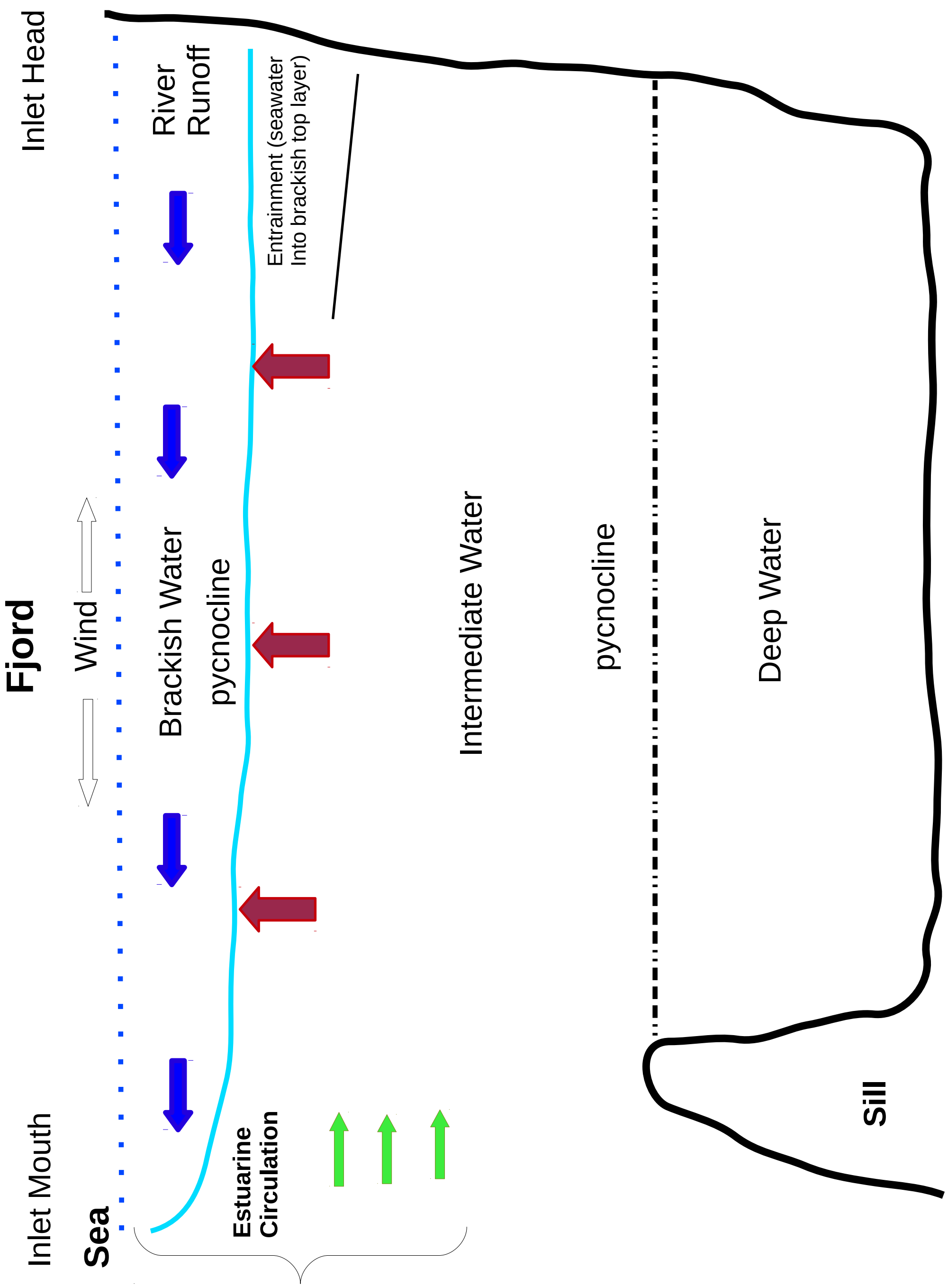

Figure 1: Longitudinal estuarine circulation in a BC fjord.

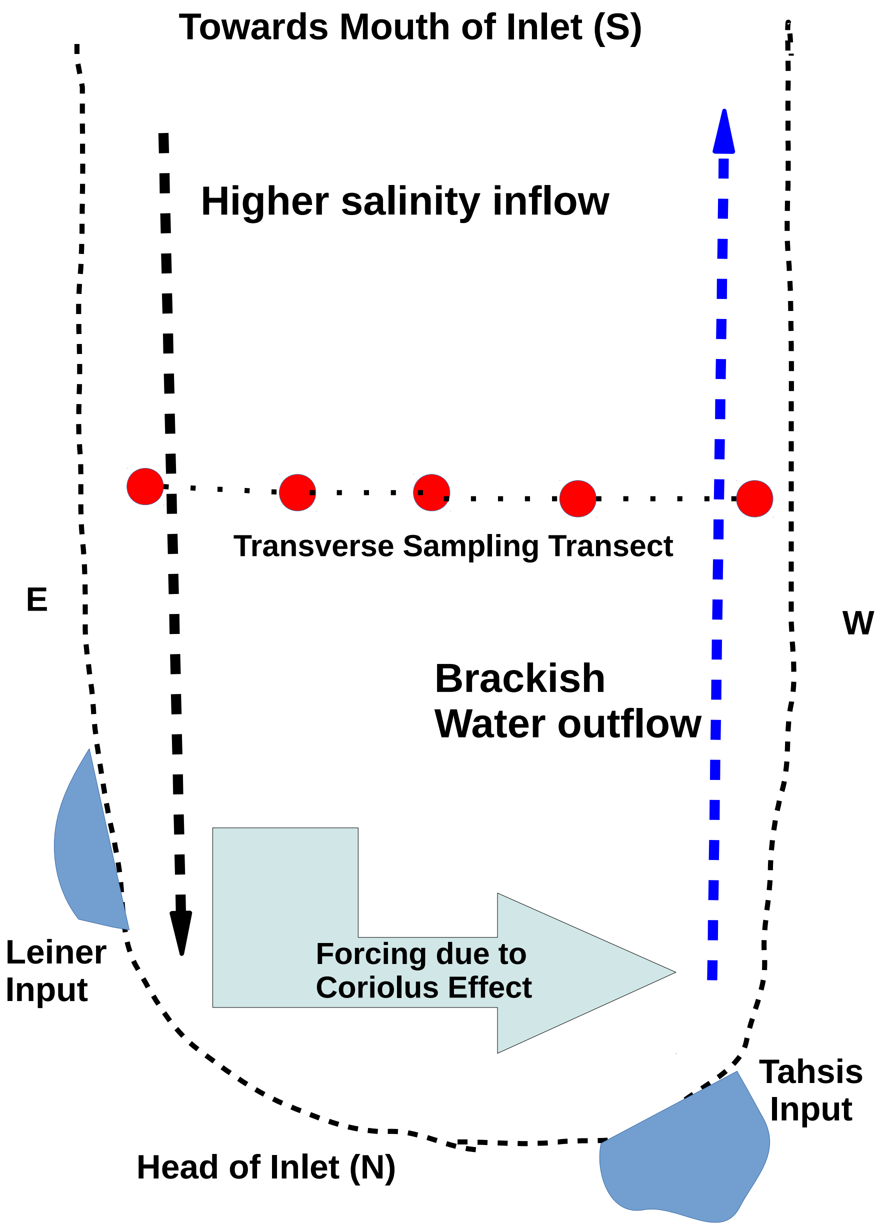

Figure 2: Transverse circulation in Tahsis Inlet.

References

[1] Claire Knox. *Are fjords sources or sinks of* CO_2*? A study of air-sea* CO_2 *fluxes in Nootka Sound, B.C.* Senior thesis, Box 357940, Seattle, Washington, May 2015.

[2] Julie Anne Koehlinger. *A Description of Water Masses in Nootka Sound and Estimation of Diffusivity (*κ*) and Upward Velocity (w) in Muchalat Inlet Using Temperature, Salinity, and Dissolved Oxygen.* Senior thesis, Box 357940, Seattle, Washington, May 2015.

[3] Robert J. Daniels. *Effect of cross channel salinity imbalance due to freshwater influence in a narrow estuary.* Senior thesis, Box 357940, Seattle, Washington, May 2015.

Glossary

σ_{T} — σ_{T}, the density of seawater, is a function of sample salinity and temperature.

CTD — an oceanographic instrument which simultaneously measures the conductivity, temperature, and depth of water in the ocean.

Geostrophic Current — geostrophic currents.