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Watershed-Coastal Connections through Mediterranean and Semi-Arid Estuaries: Physical Processes, Anthropogenic Influences, and Potential Ecological Consequences

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JOHN & MARY LOUISE RILEY SEMINAR SERIES
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Universidad de Valparaíso CHILE
CIGIDEN

CONCLUSIONS

Flow through estuaries in Mediterranean climates:

- Episodic
- Range of temporal scales need to be considered
  - Sediment flux between estuary and wetland: infragravity dominated
- Highly vulnerable to anthropogenic impacts
  - Drought, climate change effects exacerbated by humans

Bar-Built Estuarine Dynamics

An introduction:

- Mediterranean & Semi-Arid Climates
- Tides
- Waves
- Inlet Closure
- Tidal dynamics

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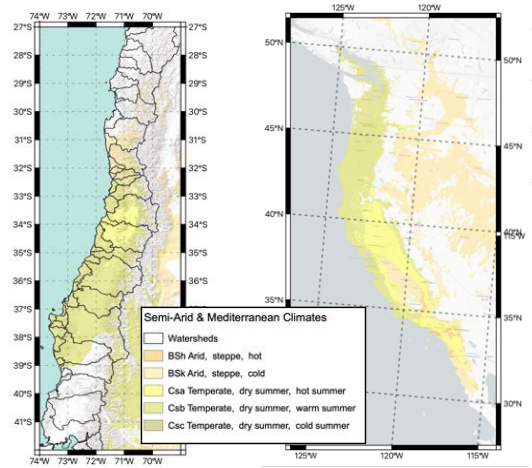

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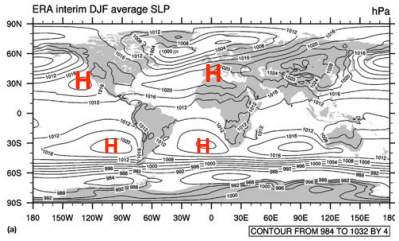
Austral Summer / Boreal Winter



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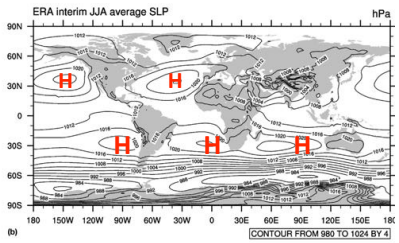

Summer in Mediterranean climates: oceanic highs prevent precipitation

Grotjahn, R. (2015). GENERAL CIRCULATION OF THE ATMOSPHERE | Mean Characteristics. In Encyclopedia of Atmospheric Sciences (pp. 73–89). Elsevier. https://doi.org/10.1016/b978-0-12-382225-3.00154-7

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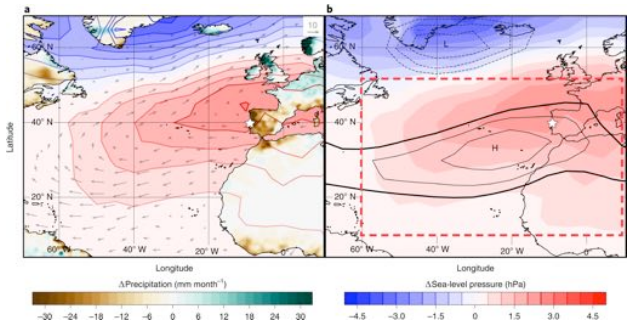

Cresswell-Clay, N., Ummenhofer, C.C., Thatcher, D.L. *et al.* Twentieth-century Azores High expansion unprecedented in the past 1,200 years. *Nat. Geosci.* **15**, 548–553 (2022). https://doi.org/10.1038/s41561-022-00971-w

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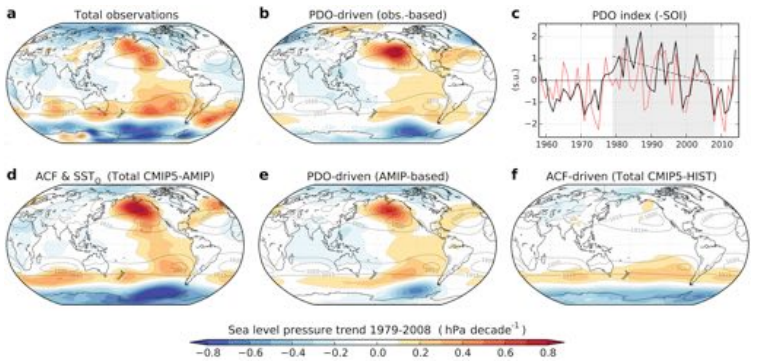

Boisier, J. P., Rondanelli, R., Garreaud, R. D., and Muñoz, F. (2016), Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile, *Geophys. Res. Lett.*, 43, 413–421, doi:10.1002/2015GL067265.

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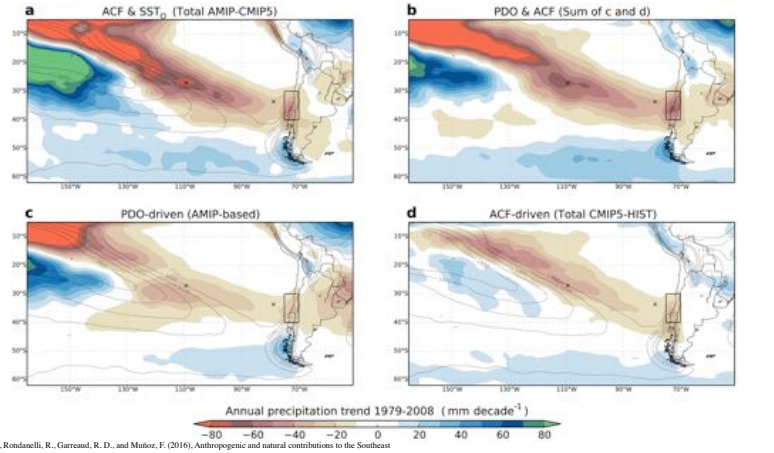

Boisier, J. P., Rondanelli, R., Garreaud, R. D., and Muñoz, F. (2016), Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile, *Geophys. Res. Lett.*, 43, 413–421, doi:10.1002/2015GL067265.

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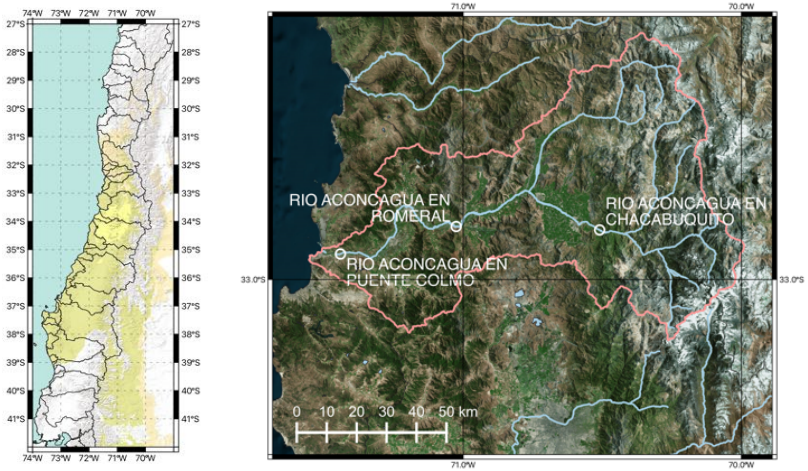

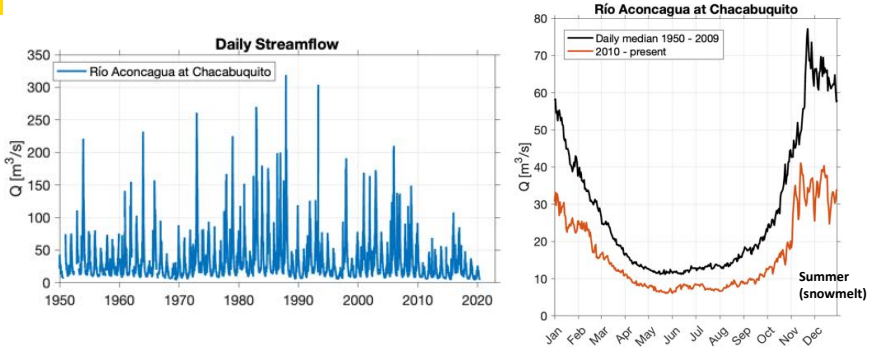

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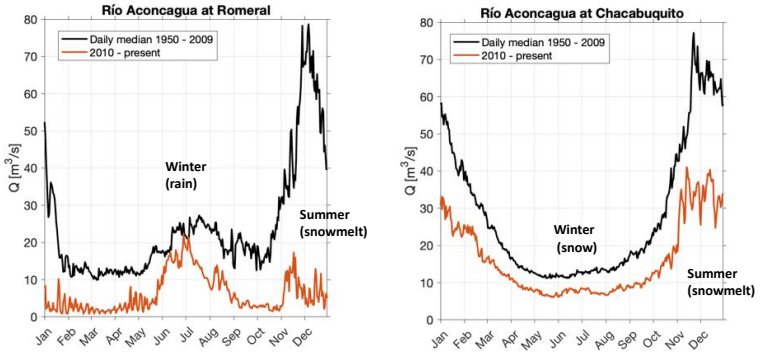
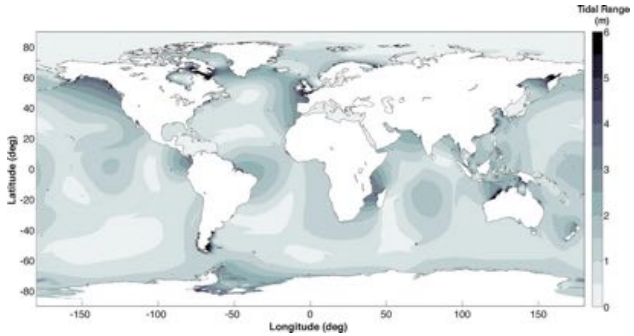
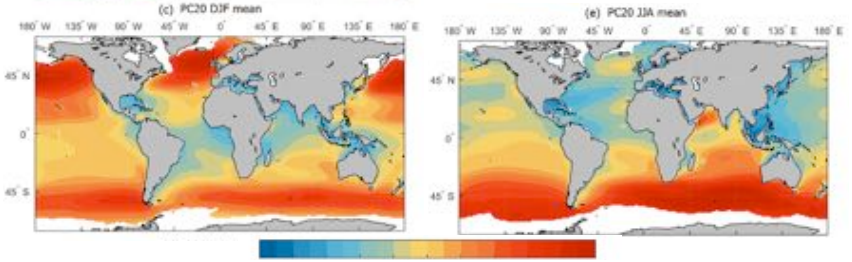




Haigh, I.D. (2016). Tidal Ranges. In: Kennish, M.J. (eds) Encyclopedia of Estuaries. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-8801-4_92

Austral Summer / Boreal Winter

Austral Winter / Boreal Summer



Lemos, G., Semedo, A., Dobrynin, M., Behrens, A., Staneva, J., Bidlot, J. R., & Miranda, P. M. (2019). Mid-twenty-first century global wave climate projections: Results from a dynamic CMIP5 based ensemble. *Global and planetary change*, *172*, 69-87.

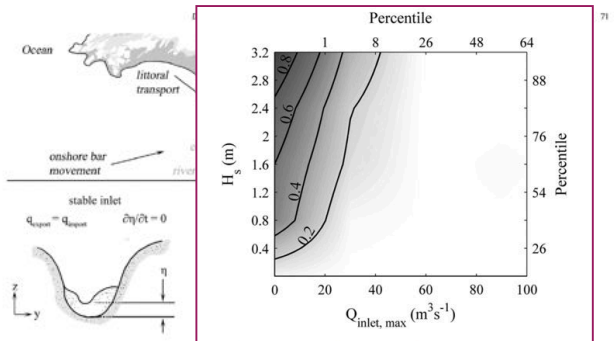
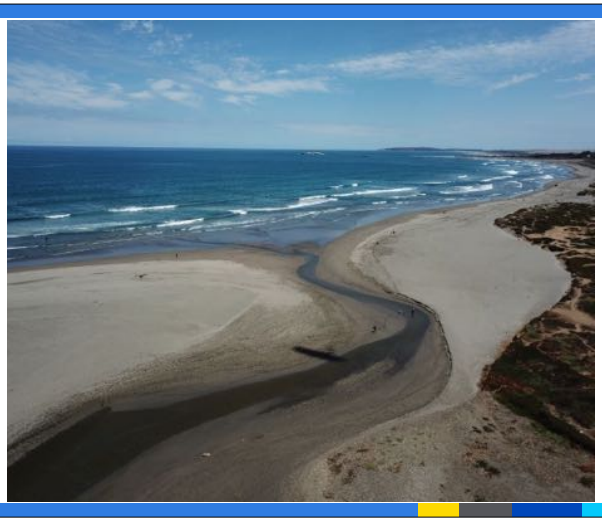
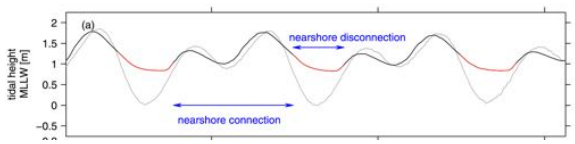
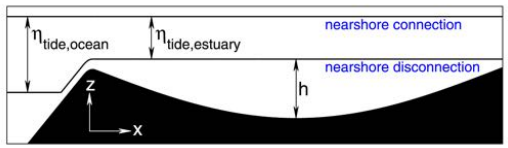


Fig. 6. Proportion of days within one day of a closure event, based on the nearshore wave height (H_s) and peak daily inlet flow ($Q_{inlet,\ max}$). This reflects data from the years 1999–2008, when a tide gage was operated within the estuary. Except during winter, the majority of $Q_{inlet,\ max}$ is associated with tides.

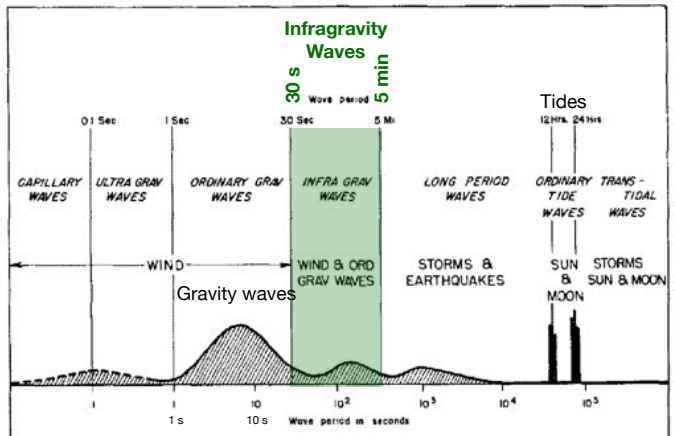
Behrens, D.K., Bombardelli, F.A., Largier, J.L. and Twohy, E. 2013. Episodic closure of the tidal inlet at the mouth of the Russian River — A small bar-built estuary in California. *Geomorphology*, *189*, pp. 66—80. doi: 0.1016/j.geomorph.2013.01.017



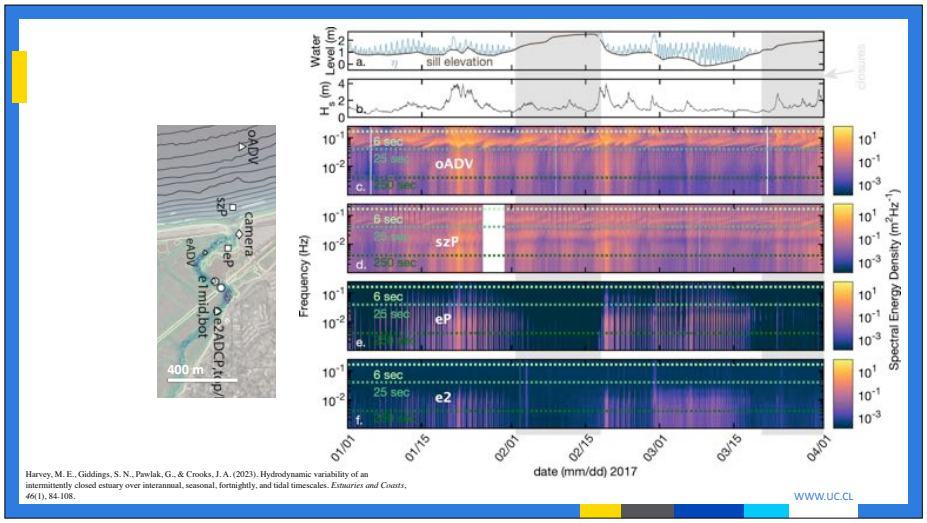




(Williams & Stacey, 2016 JGR-Oceans)

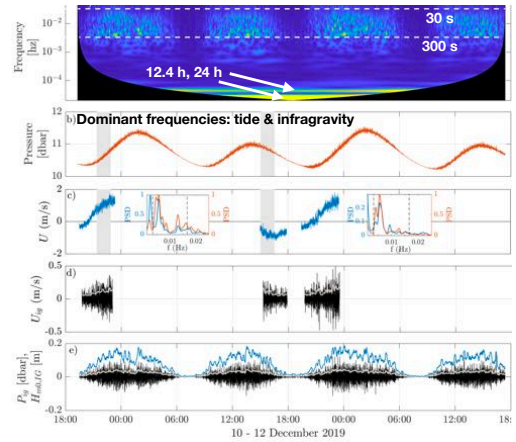


(Munk, 1950)



Harvey, M. E., Giddings, S. N., Pawlak, G., & Crooks, J. A. (2023). Hydrodynamic variability of an intermittently closed estuary over interannual, seasonal, fortnightly, and tidal timescales. *Estuaries and Coasts*, *46*(1), 84-108.

Wavelet analysis of pressure sensor (Maipo inlet, Dec. 2019):



Infragravity (IG) energy:

- **Important in small bar-built estuarine hydrodynamics (Williams & Stacey, 2016), plume dynamics (Flores et al. 2022)**
- **Gravity waves break in nearshore, inlet acts as low-pass filter for IG**

(Flores, Williams, and Horner-Devine, 2022, GRL)

Suspended sediment dynamics

Anthropogenic processes are changing sediment load to the coast

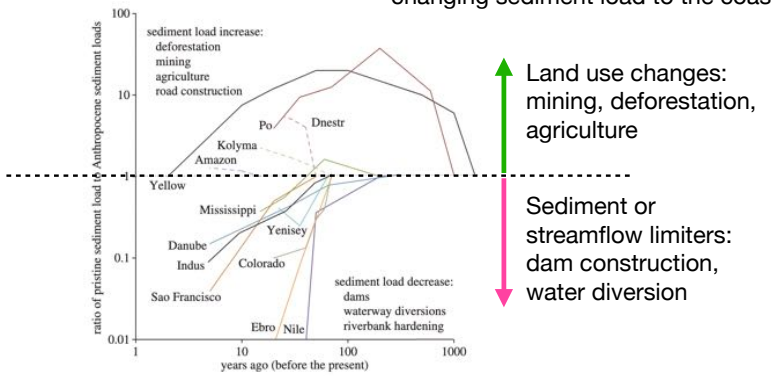
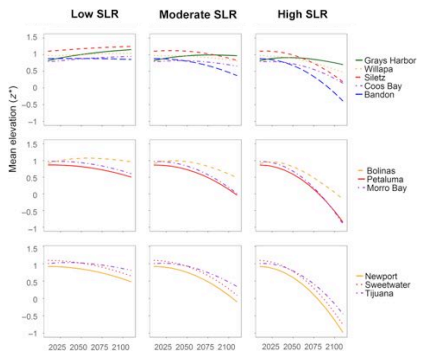


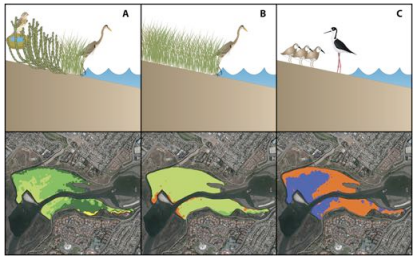
Figure 5. Relative changes in the sediment loads carried by select rivers. Note that climate variability has been removed from these trends, by taking averages across 10–20 years.

(Syvitsky & Kettner, 2011)



Sea level rise scenarios - 100 % loss of coastal marshes in California by 2100.

- Lack of sediment flux
- Lack of space for marsh migration



(Thorne et al. 2018)

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Maipo Estuary, Central Chile

17 - 22 January 2022

Wetlands in Mediterranean climates (e.g. California, Chile, Australia, South Africa) -

Soils have low organic content - wetland accretion requires sediment delivery from watershed

To keep up with sea level rise, suspended sediment delivery required.

How is sediment delivered from estuary (watershed) to the wetland?

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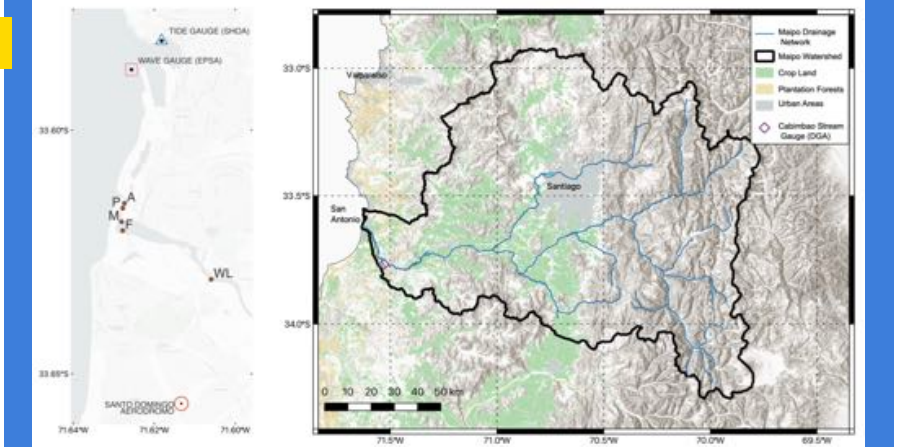

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Estuary - Río Maipo, Central Chile

(-33.6, -71.6)

Andean watershed, includes Santiago, agriculture

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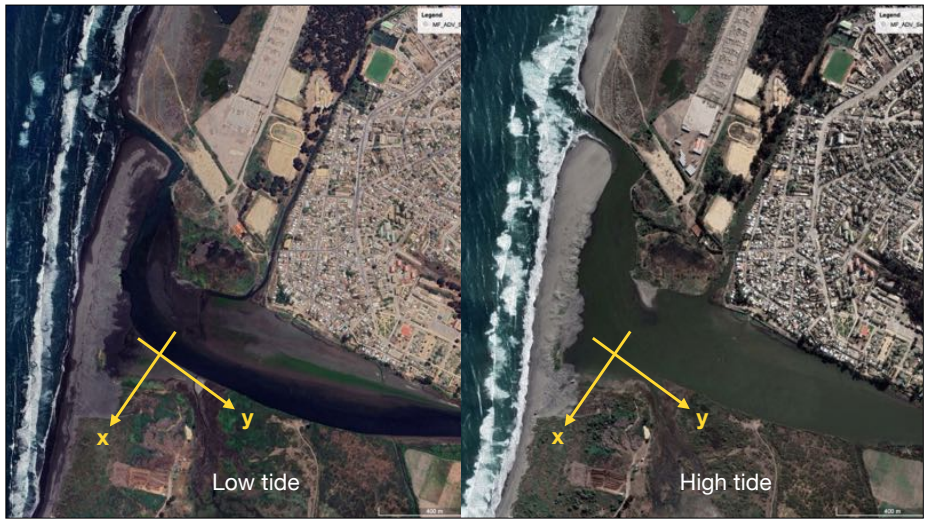
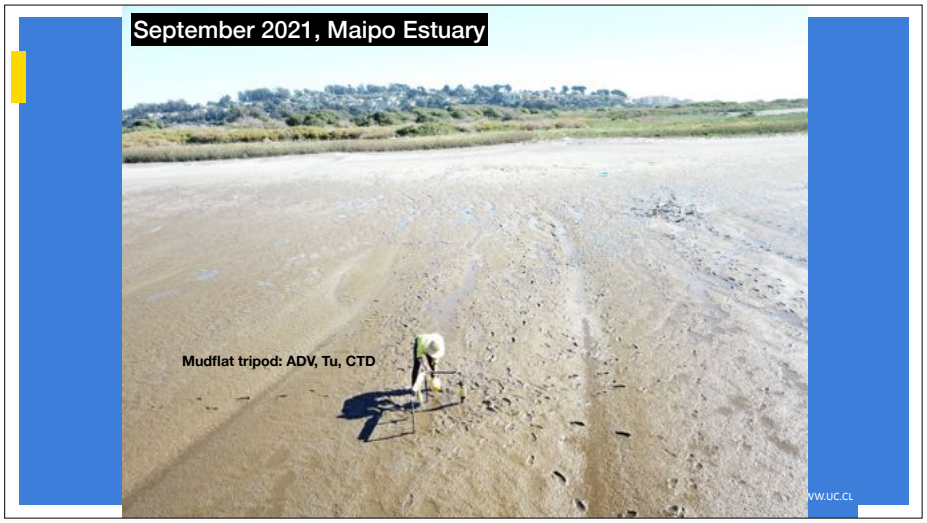
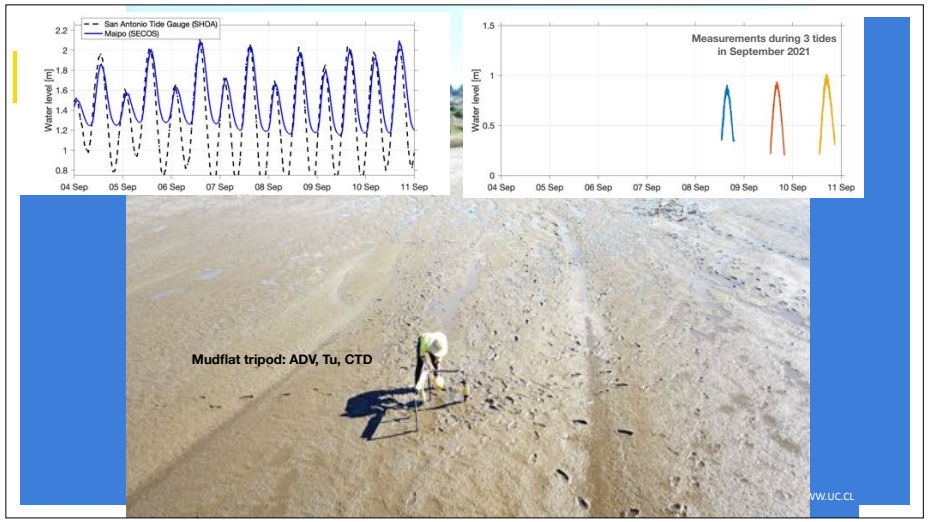
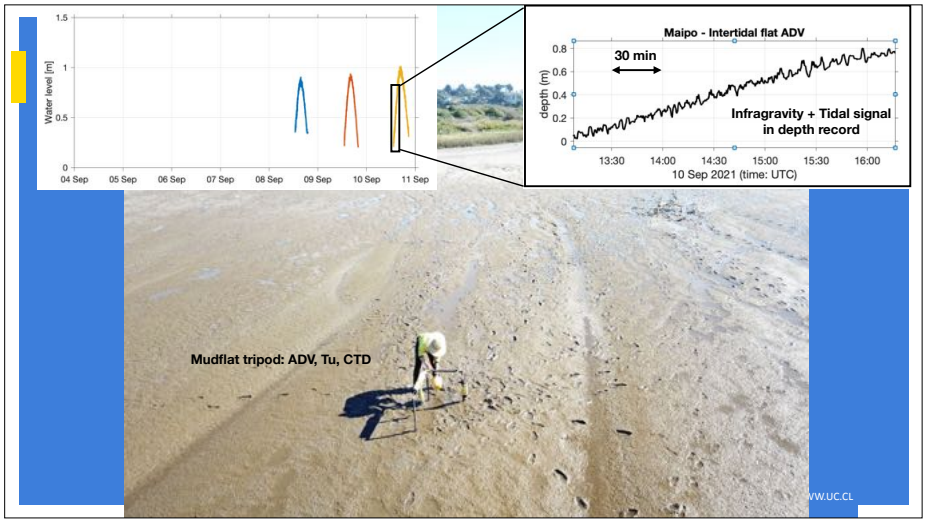
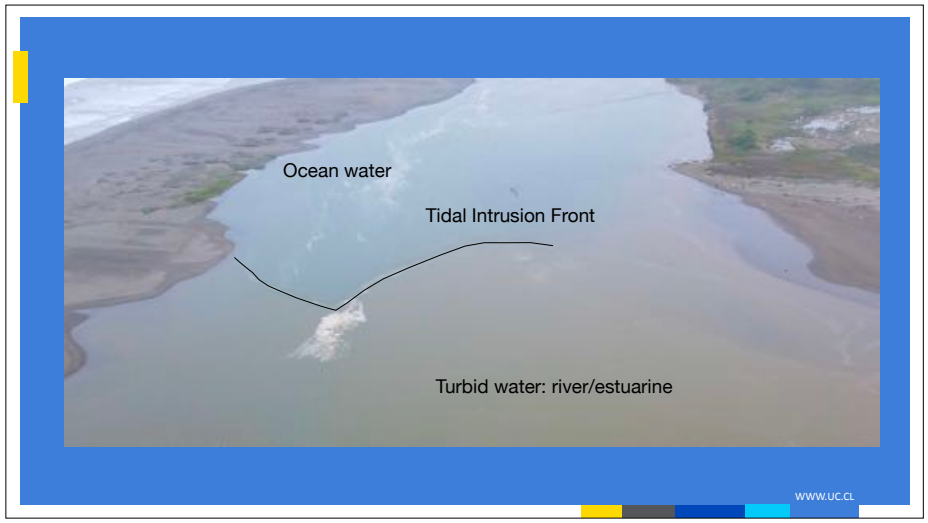

x
y
Low tide
x
y
High tide


September 2021, Maipo Estuary
Mudflat tripod: ADV, Tu, CTD


San Antonio Tide Gauge (SHOA)
Maipo (SECOS)
Water level [m]
Measurements during 3 tides
in September 2021
Mudflat tripod: ADV, Tu, CTD


Water level [m]
Maipo - Intertidal flat ADV
30 min
depth (m)
Infragravity + Tidal signal
in depth record
10 Sep 2021 (time: UTC)
Mudflat tripod: ADV, Tu, CTD


Ocean water
Tidal Intrusion Front
Turbid water: river/estuarine
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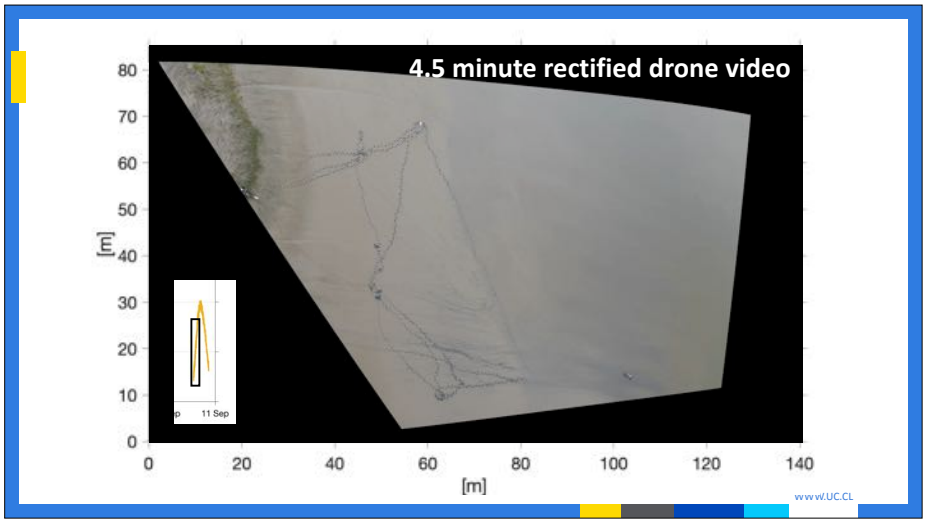
4.5 minute rectified drone video
[m]
[m]
0
10
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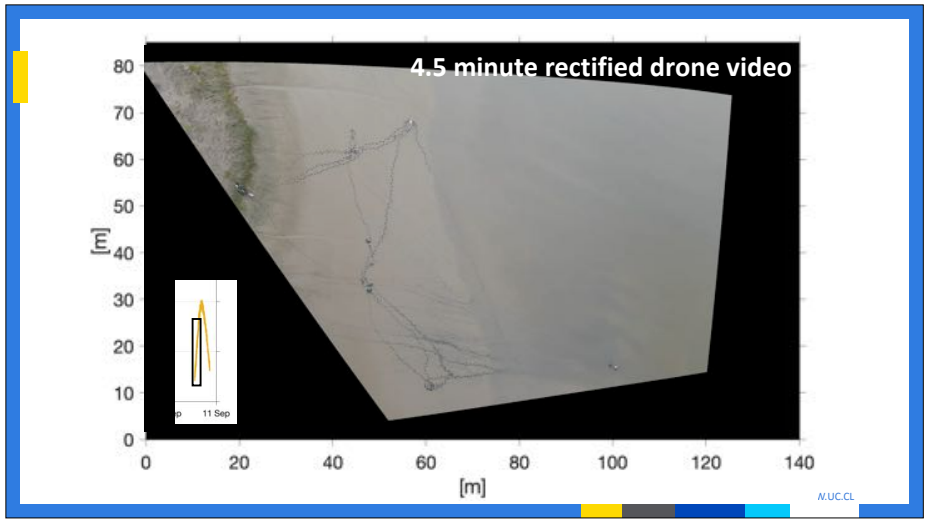
30
40
50
60
70
80
0
20
40
60
80
100
120
140
11 Sep
www.UC.CL


4.5 minute rectified drone video
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11 Sep
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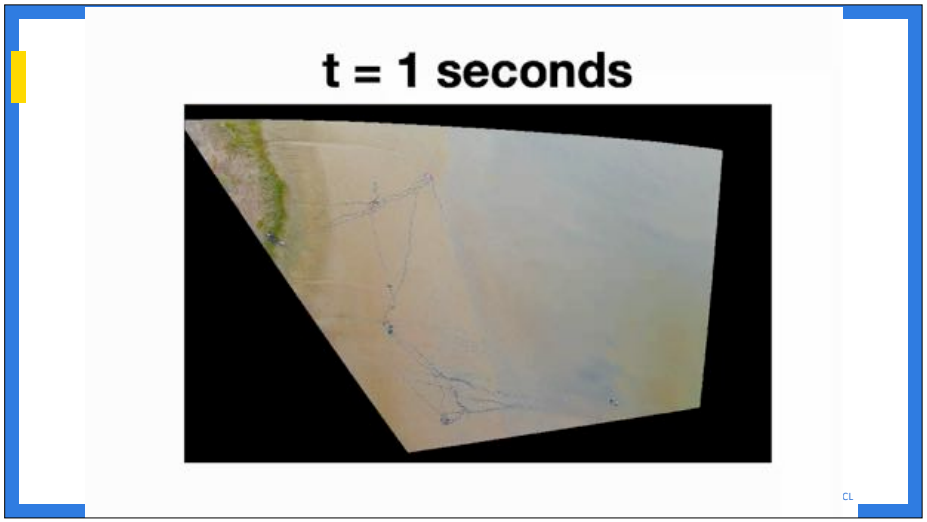
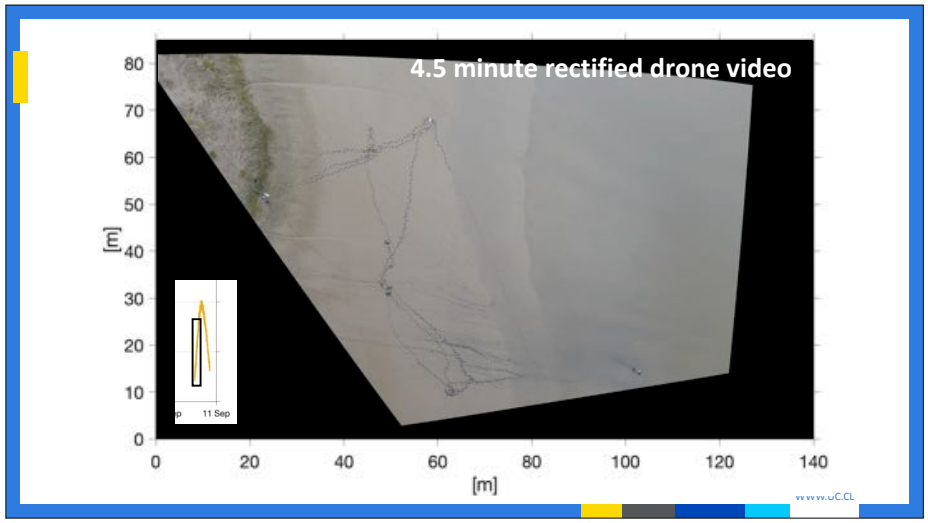
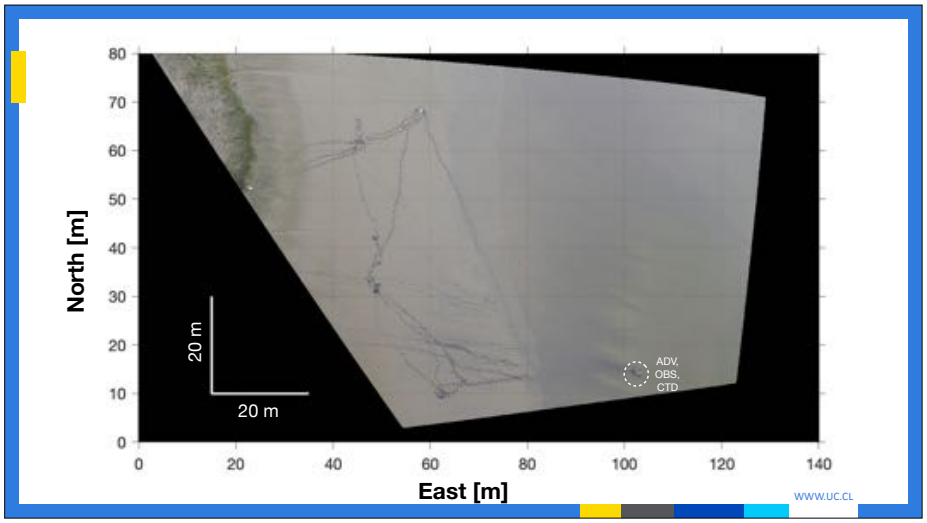
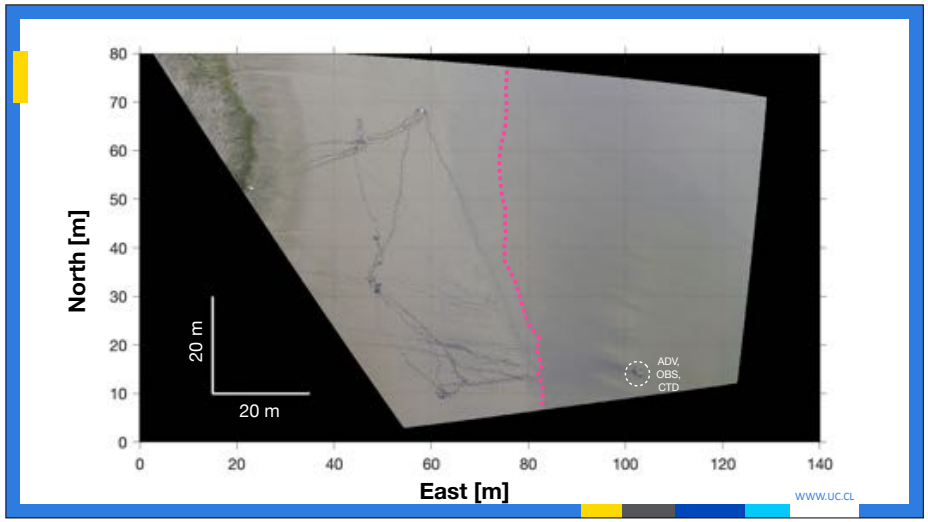

t = 1 seconds
CL


4.5 minute rectified drone video
[m]
[m]
11 Sep


North [m]
East [m]
20 m
20 m
ADV,
OBS,
CTD
WWW.UC.CL


North [m]
East [m]
20 m
20 m
ADV,
OBS,
CTD
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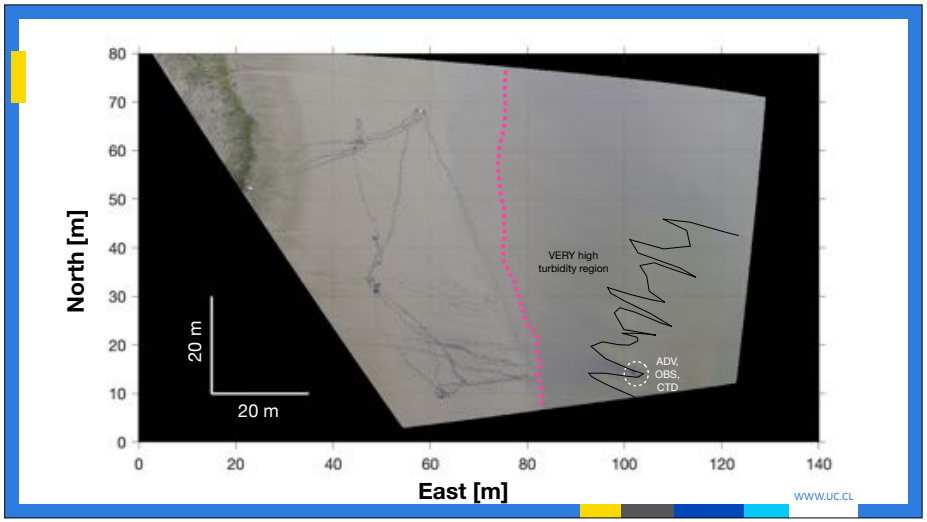
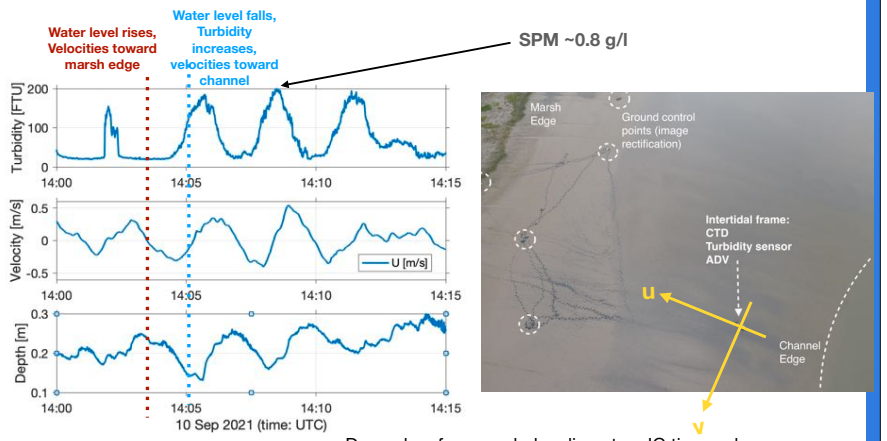
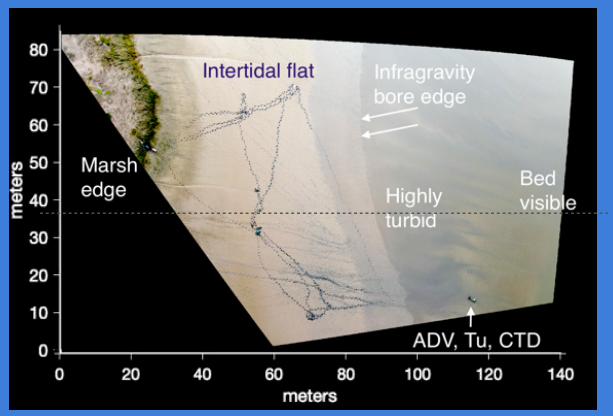
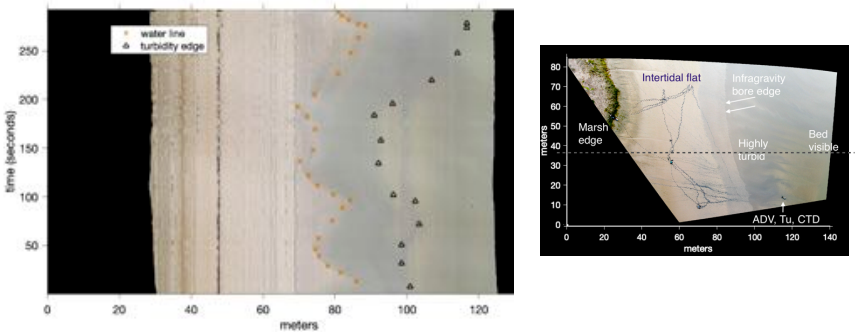

North [m]
East [m]
VERY high
turbidity region
20 m
20 m
ADV,
OBS,
CTD
WWW.UC.CL



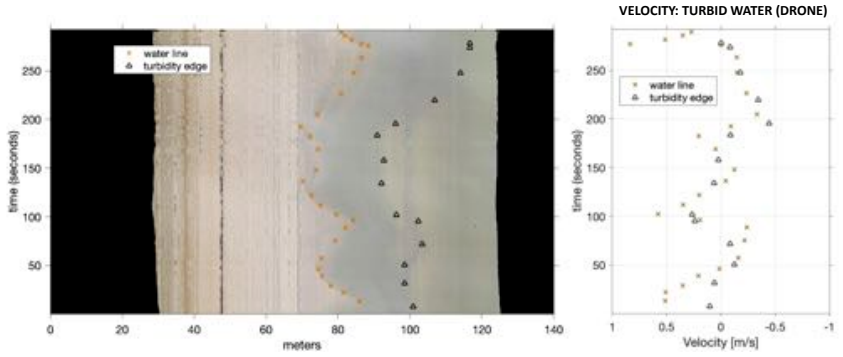
15 minute interval (rising tide)

Do peaks of suspended sediment on IG timescales contribute to flux of sediment across intertidal mudflat?

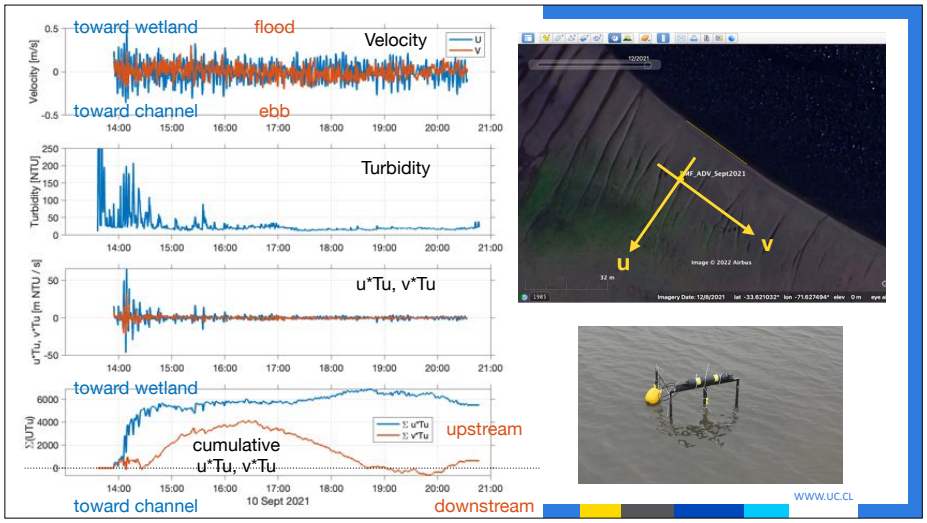


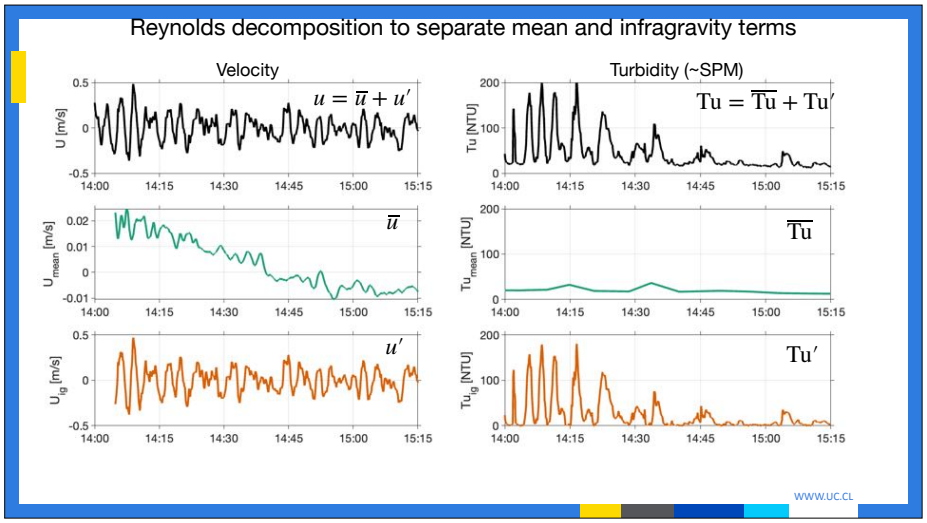


VELOCITY: TURBID WATER (DRONE)



INFRAGRAVITY VELOCITIES - MOVING SEDIMENT UP AND DOWN INTERTIDAL FLAT: IS THERE TRANSPORT?


toward wetland
flood
Velocity
toward channel
ebb
Turbidity
u*Tu, v*Tu
toward wetland
cumulative
u*Tu, v*Tu
upstream
toward channel
10 Sept 2021
downstream
u
v
WWW.UC.CL


Reynolds decomposition to separate mean and infragravity terms
Velocity
Turbidity (~SPM)
$u = \overline{u} + u'$
$\mathrm{Tu} = \overline{\mathrm{Tu}} + \mathrm{Tu}'$
$\overline{u}$
$\overline{\mathrm{Tu}}$
u'
Tu'
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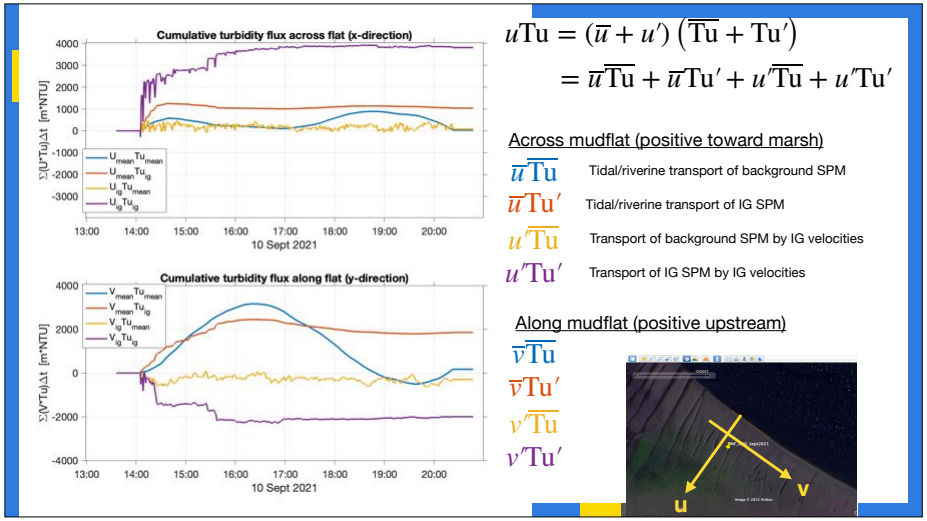
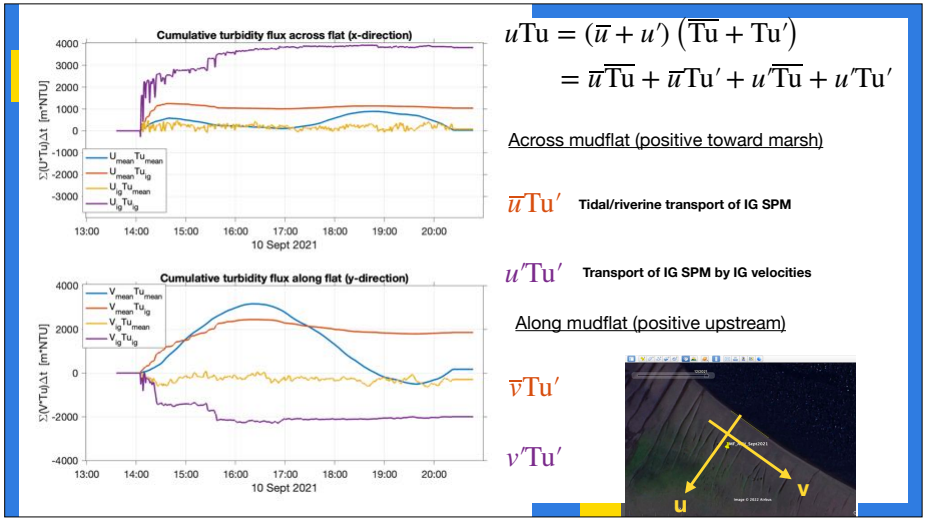
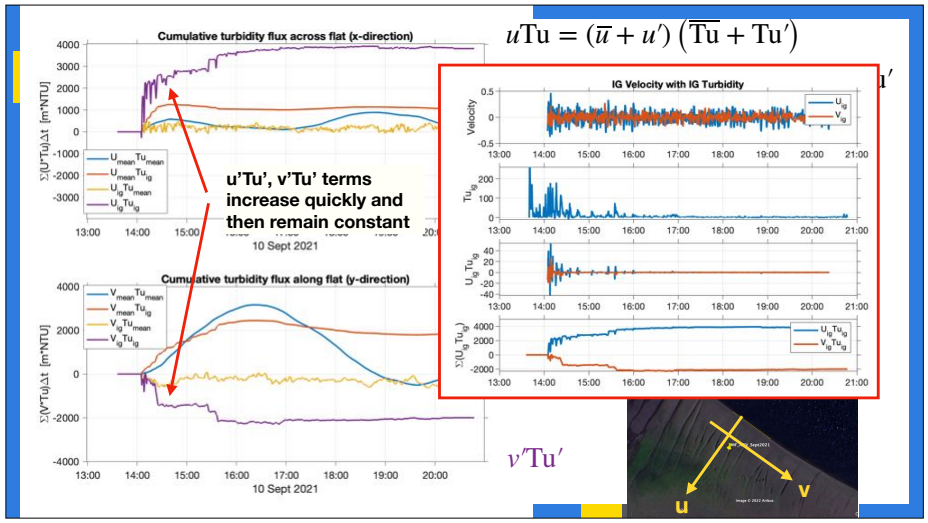
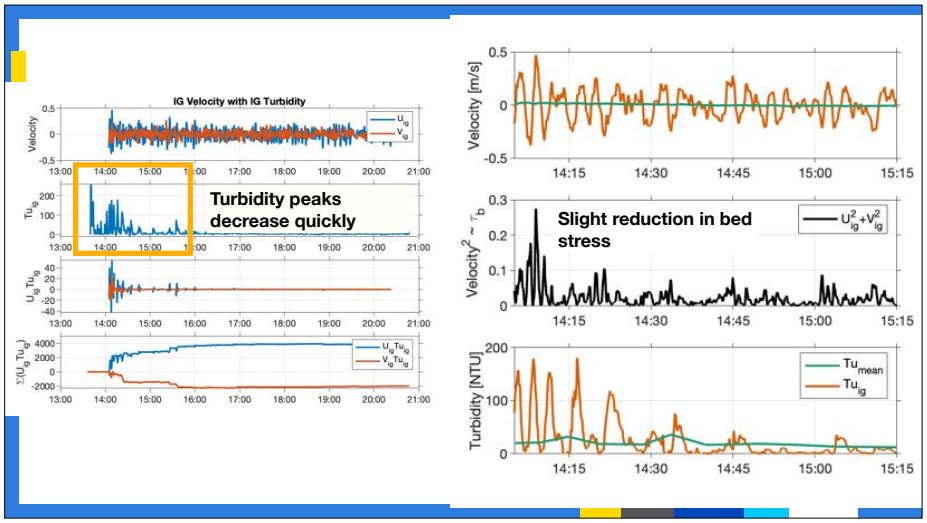

Cumulative turbidity flux across flat (x-direction)
Cumulative turbidity flux along flat (y-direction)
10 Sept 2021
$u\mathrm{Tu} = (\overline{u} + u')\left(\overline{\mathrm{Tu}} + \mathrm{Tu}'\right)$
$= \overline{u}\,\overline{\mathrm{Tu}} + \overline{u}\mathrm{Tu}' + u'\overline{\mathrm{Tu}} + u'\mathrm{Tu}'$
Across mudflat (positive toward marsh)
$\overline{u}\,\overline{\mathrm{Tu}}$ Tidal/riverine transport of background SPM
$\overline{u}\mathrm{Tu}'$ Tidal/riverine transport of IG SPM
$u'\overline{\mathrm{Tu}}$ Transport of background SPM by IG velocities
$u'\mathrm{Tu}'$ Transport of IG SPM by IG velocities
Along mudflat (positive upstream)
$\overline{v}\,\overline{\mathrm{Tu}}$
$\overline{v}\mathrm{Tu}'$
$v'\overline{\mathrm{Tu}}$
$v'\mathrm{Tu}'$
u
v

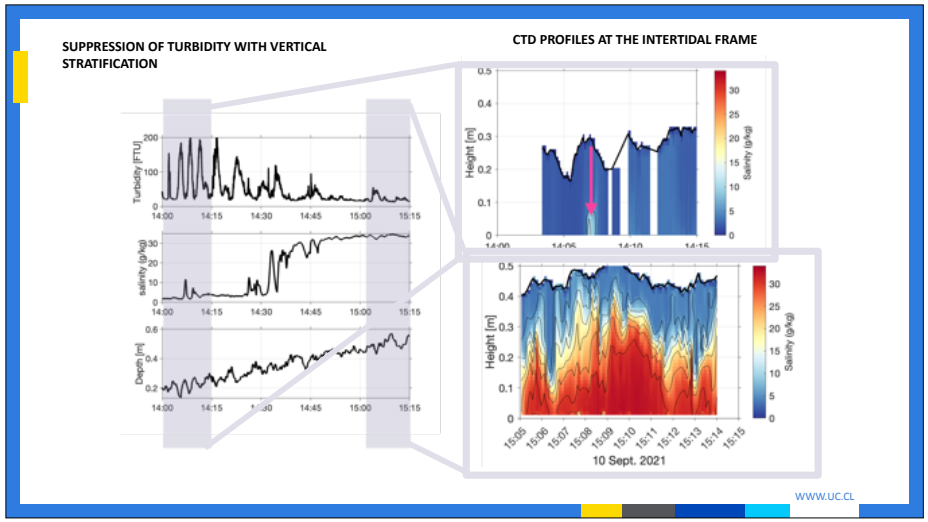

Cumulative turbidity flux across flat (x-direction)
Cumulative turbidity flux along flat (y-direction)
10 Sept 2021
$u\mathrm{Tu} = (\overline{u} + u')\left(\overline{\mathrm{Tu}} + \mathrm{Tu}'\right)$
$= \overline{u}\,\overline{\mathrm{Tu}} + \overline{u}\mathrm{Tu}' + u'\overline{\mathrm{Tu}} + u'\mathrm{Tu}'$
Across mudflat (positive toward marsh)
$\overline{u}\mathrm{Tu}'$ Tidal/riverine transport of IG SPM
$u'\mathrm{Tu}'$ Transport of IG SPM by IG velocities
Along mudflat (positive upstream)
$\overline{v}\mathrm{Tu}'$
$v'\mathrm{Tu}'$
u
v



$$u\mathrm{Tu} = (\overline{u} + u')\left(\overline{\mathrm{Tu}} + \mathrm{Tu}'\right)$$

$$v'\mathrm{Tu}'$$





SHORT TIMESCALE SEDIMENT DYNAMICS

- Infragravity (IG) oscillations in bar-built estuaries contribute to sediment resuspension on intertidal flats.
- Sediment (turbidity) fluxes between the estuary and salt-marsh are dominated by the IG components
- Mudflat resuspension highest early in flood, possibly limited by salt-stratification.

LONG TIMESCALE SEDIMENT DYNAMICS?

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Río Aconcagua, Chile (32.9S,71.5W)

(R. Flores)

Pescadero Creek, California (37.2N,122.4W)

Pescadero estuary, California

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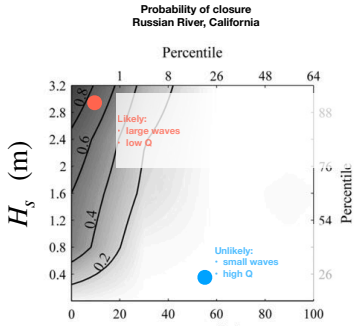
Dominant variables in inlet closure

river tidal

$$Q_{inlet} = Q_r + A_s \frac{d\eta}{dt}$$

tidal estuarine area x tidal height / time

- Inlet velocity depends on river flow and tidal flow
- In the Russian River - inlet closure probability increases with small inlet flow and large waves



Behrens, D.K., Bombardelli, F.A., Largier, J.L, and Twohy, E. 2013. Episodic closure of the tidal inlet at the mouth of the Russian River — A small bar-built estuary in California. *Geomorphology*, *189*, pp. 66—80. doi: 0.1016/j.geomorph.2013.01.017

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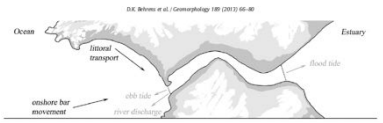
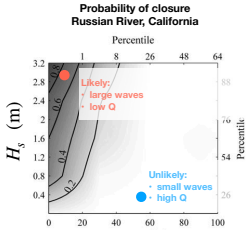


Inlet Stability:
• Waves accrete sediment
• Inlet flow (river + tidal) scours

$$H_s \text{ vs. } Q_r + A_s \frac{d\eta}{dt}$$



Behrens, D.K., Bombardelli, F.A., Largier, J.L, and Twohy, E. 2013. Episodic closure of the tidal inlet at the mouth of the Russian River — A small bar-built estuary in California. *Geomorphology*, *189*, pp. 66—80. doi: 0.1016/j.geomorph.2013.01.017

(Behrens et al., 2013; Williams, 2014)

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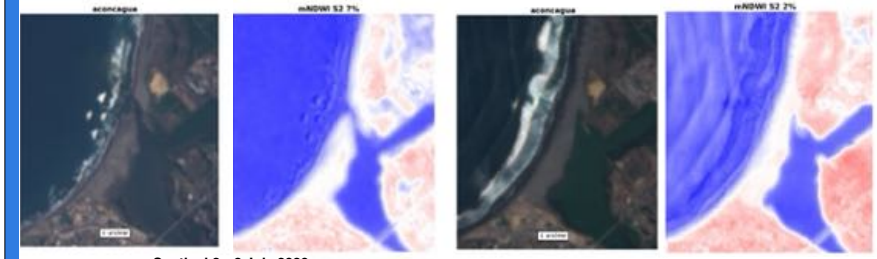
Satellite time series: Landsat 5-8, Sentinel-2: 1985 - present

InletTracker toolbox (Heimhuber et al. 2021) - is a python toolbox that uses Google Earth Engine to obtain Landsat and Sentinel-2 data, and calculates water indices to determine intermittently-closed estuary inlet state.

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

$$mNDWI = \frac{Green - SWIR1}{Green + SWIR1}$$

Here, the modified Normalized Difference Water Index is shown for two cases in 2020 to show closed and open conditions.

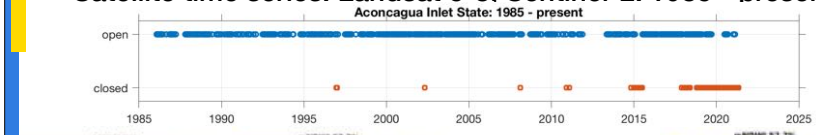


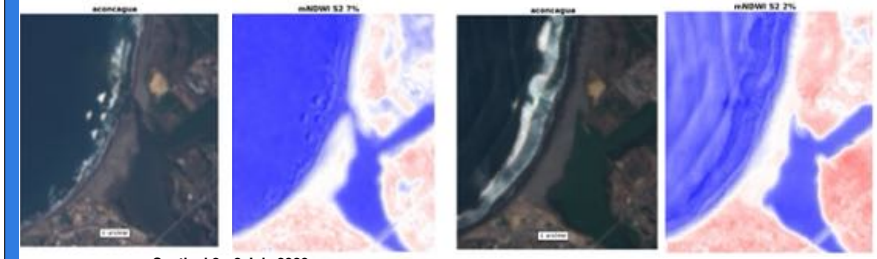
Sentinel 2 - 2 July 2020
Open inlet

Sentinel 2 - 9 January 2020
Closed inlet

Heimhuber, V., Vos, K., Fu, W. and Glamore, W., 2021. InletTracker: An open-source Python toolkit for historic and near real-time monitoring of coastal inlets from Landsat and Sentinel-2. *Geomorphology*, p.107830.

Satellite time series: Landsat 5-8, Sentinel-2: 1985 - present





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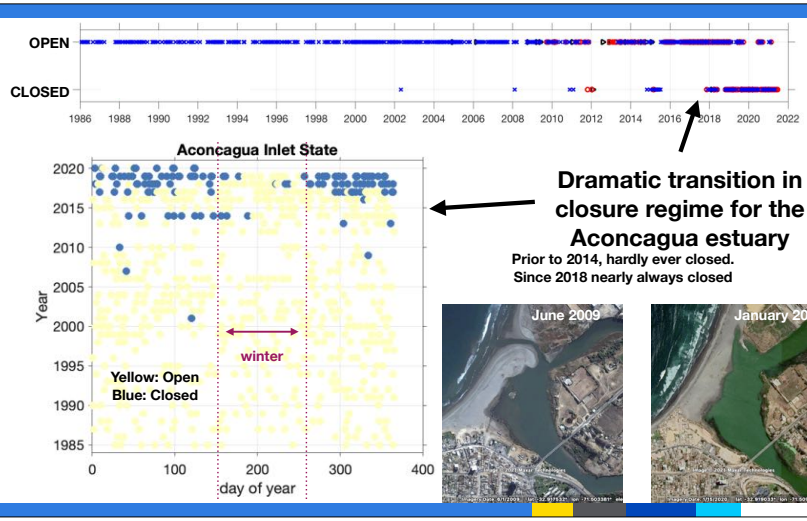


Dramatic transition in closure regime for the Aconcagua estuary

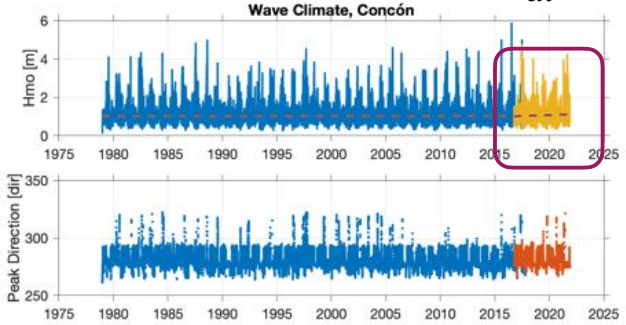
Prior to 2014, hardly ever closed.
Since 2018 nearly always closed

Wave climate H_s vs. $Q_r + A_s \frac{d\eta}{dt}$

Wave model: Sebastian Correa, UV Centro de Alerta de Marejadas

Inlet stability: H_s vs. Q_{inlet}

Wave climate H_s vs. $Q_r + A_s\frac{d\eta}{dt}$



slight trend ~ 1.9 cm/year 2016 - present

Wave model: Sebastian Correa, UV Centro de Alerta de Marejadas

Inlet stability: H_s vs. Q_{inlet}

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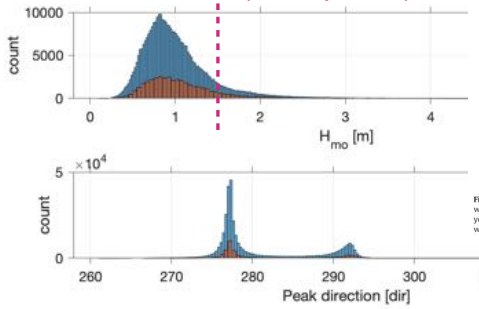
Wave climate

Australian ICOLL limit: 100 y mean Hs (McSweeney et al. 2017)



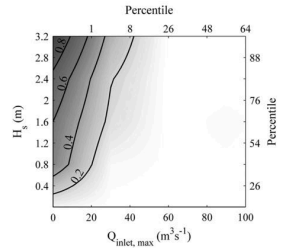


Fig. 6. Proportion of days within one day of a closure event, based on the nearshore wave height (H_s) and peak daily inlet flow ($Q_{inlet,\ max}$). This reflects data from the years 1999–2008, when a tide gage was operated within the estuary. Except during winter, the majority of $Q_{inlet,\ max}$ is associated with tides.

Wave climate: sufficiently large for coastal sediment transport capable of closing inlets.

Wave model: Sebastian Correa, UV Centro de Alerta de Marejadas

Other (smaller) estuaries along the coast are often closed

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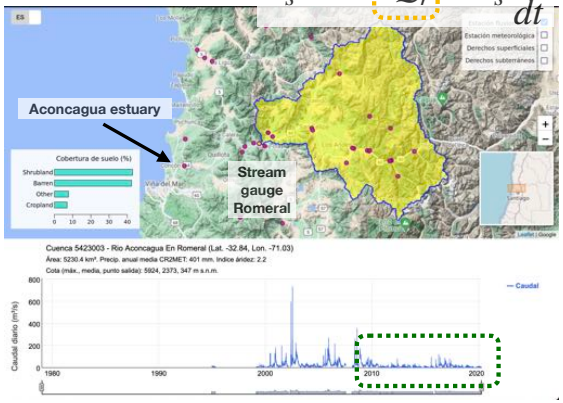
Streamflow H_s vs. $Q_r + A_s\frac{d\eta}{dt}$



Streamflow: Dirección General de Agua (dga.cl), CAMEL-CL https://www.cr2.cl/eng/camels/

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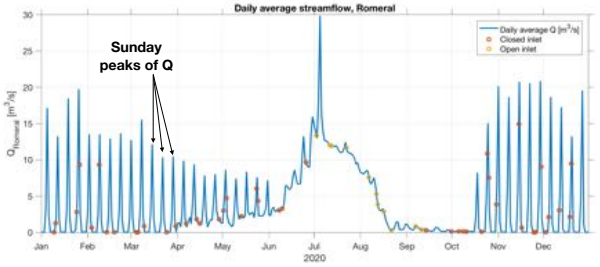
Streamflow Qr ~ 0 m³ H_s vs. $Q_r + A_s\frac{d\eta}{dt}$



- Streamflow at the Romeral gauge shows a seasonal cycle AND the effects of water management
- Streamflow is reduced to zero, with peaks on Sundays
- Discharge depends on system of irrigation canals

Streamflow: Dirección General de Agua (dga.cl), CAMEL-CL https://www.cr2.cl/eng/camels/

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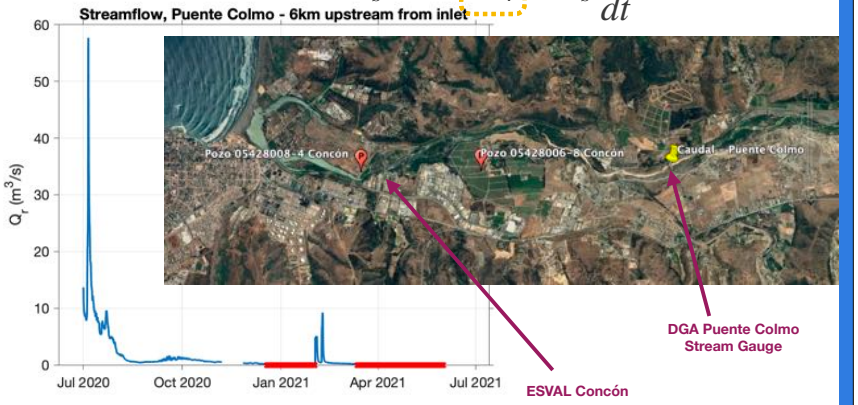
Streamflow Q_r ~ 0 m³ H_s vs. $Q_r + A_s\frac{d\eta}{dt}$



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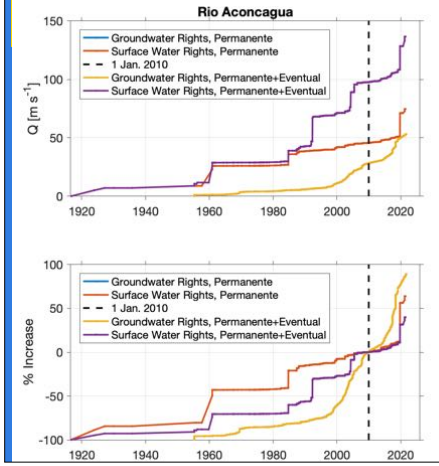
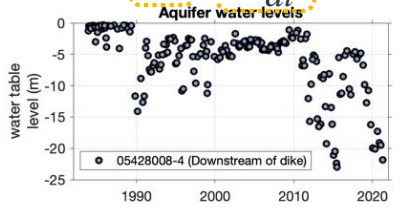
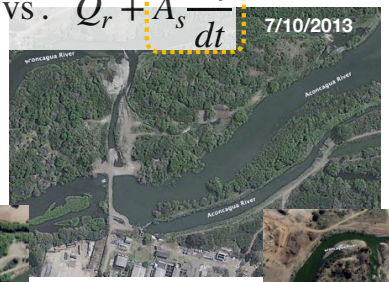
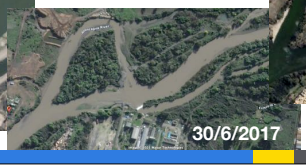
Streamflow Q_r ~ 0 m³ H_s vs. $Q_r + A_s\frac{d\eta}{dt}$





Altered tidal prism H_s vs. $Q_r + A_s\frac{d\eta}{dt}$





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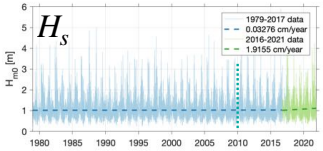
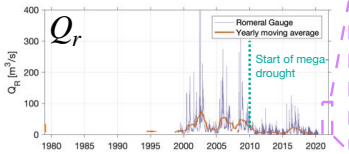
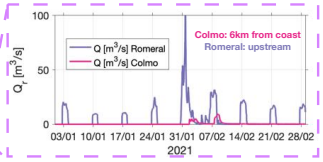
Waves vs. Inlet Flow: H_s vs. $Q_r + A_s\frac{d\eta}{dt}$

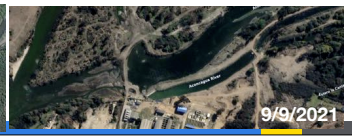






Why have we seen this transition from a usually open to a usually closed inlet?

- The wave climate has slightly increased, but is already sufficiently large to prompt inlet closure in smaller systems
- The streamflow has been reduced by drought AND by water management: newly installed downstream gauge shows $Q_r = 0$ m³/s.
- With increased water use, a dike has been constructed 2.5 km upstream from the inlet, changing the tidal prism and thus tidal flow through the inlet.



Shift in *normal* is related to climate change and drought, but caused by poor management of water resources.

Implications include lack of freshwater, watershed sediment, nutrients to wetlands, the coast, and coastal ecosystems.

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https://www.latercera.com/que-pasa/noticia/zanja-milagrosa-rio-maipo-vuelve-a-desembocar-en-el-mar/WZ6SODMJNZESHMI4DTUH6NKP7Y/

CONCLUSIONS

Flow through estuaries in Mediterranean climates:

- Episodic
- Range of temporal scales need to be considered
  - Sediment flux between estuary and wetland: infragravity dominated
- Highly vulnerable to anthropogenic impacts
  - Drought, climate change effects exacerbated by humans

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