1. Scientific Goals

The Benthic and Pelagic fluxes play a crucial role in governing coastal waters dynamics.

2. Model setup

NEMO – BFM 1D Configuration + embedded BPC submodel

3. Implementation sites

Experiments design

- N. 3 implemented sites
- N. 2 Experiments (Comparison)

4. Gulf of Trieste (MA21)

Simulated Inorganic Nutrients affect Chl-a dynamic (mainly at depth, 78m).

5. St. Helena Bay (SHB)

Inorganic Nutrients seasonal improvements positively affect Chl-a dynamic (Normalized Mean Seas. Bias)

6. Svynøy Fyr (SFyr)

Chlorophyll dynamic is related to nutrients dynamic and light limitation (JFM). (Normalized Mean Seas. Bias)

7. Sensitivity Analisys

Different degree of sensibility to the B-C fluxes (RMSE spread) and to site-specific characteristics.

8. Conclusions

- Model improvements in reproducing B-P fluxes;
- Different sedimentation-remineralization scenarios
To implement and test a numerical model addressing benthic dynamics and BPC processes.

To assess the skills of one-dimensional coupled physical-biogeochemical models in simulating the BPC.

Evaluate ecosystem dynamics in three marine areas with different climatic and ecological characteristics.

Limited knowledge about the exchange rates between the two habitats (Griffiths et al., 2017)

Availability of data (Soetaert et al., 2000, Griffiths et al., 2017)

Benthic-pelagic fluxes neglected or approximated to a simple closure term (Soetaert et al., 2000)

Coastal waters host the world’s most productive ecosystems, providing:

- 30% of the global primary production;
- 80% of the organic matter burial;
- ~30% of atmospheric CO$_2$ sink (6% -11% anthropogenic CO$_2$ sink).

(Borges et al., 2011, Hardison et al., 2017)

Benthic activity play an important role in determining the pelagic biogeochemical characteristics of coastal waters (Soetaert et al., 2000, Griffiths et al., 2017).

The physically mediated exchanges structuring the BPC are constituted by the sinking and resuspension fluxes of particulate organic matter and by the diffusion of inorganic nutrients.
1-D configuration

Methodological approach

\[
\frac{\partial A}{\partial t} = \frac{\partial A}{\partial t}_{phys} + \frac{\partial A}{\partial t}_{bio}
\]

A = generic state variable

Benthic-Pelagic Sub-model

\[
\frac{dQ_{j}^{(1,6)}}{dt}_{sed} = -\omega_{bur} \left[ R_{j}^{(1,6)} + (\xi_{j} - \xi_{j}) \sum_{i=1,4} P_{i,j} \right]_{z=z_{b}}
\]

Burial and remineralization parameters

<table>
<thead>
<tr>
<th>(\omega, \mu)</th>
<th>Partitioning coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\xi_{j})</td>
<td></td>
</tr>
<tr>
<td>(R_{j}^{(1)})</td>
<td>Pelagic dissolved organic matter</td>
</tr>
<tr>
<td>(R_{j}^{(6)})</td>
<td>Pelagic particulate organic matter</td>
</tr>
<tr>
<td>(P_{j})</td>
<td>Phytoplankton</td>
</tr>
<tr>
<td>(Q_{j}^{(1)})</td>
<td>Benthic dissolved matter</td>
</tr>
</tbody>
</table>

\[ \frac{dQ_{j}^{(1,6)}}{dt}_{rmn/diff} = \mu_{Q_{j}^{(1,6)}} Q_{j}^{(1,6)}_{z=z_{b}} \]
<table>
<thead>
<tr>
<th>Implementation site</th>
<th>Experiments design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site:</strong> SFyr</td>
<td><strong>NO-RM</strong></td>
</tr>
<tr>
<td><strong>Maximum Depth [m]</strong></td>
<td>Sinking</td>
</tr>
<tr>
<td>150</td>
<td>Burial</td>
</tr>
<tr>
<td><strong>Atmospheric Forcing</strong></td>
<td>Remineralization</td>
</tr>
<tr>
<td>ERA5</td>
<td><strong>BPC_RETURN</strong></td>
</tr>
<tr>
<td><strong>Observations</strong></td>
<td>Sinking</td>
</tr>
<tr>
<td>PO4; NO3; Chl-a; SiO4;</td>
<td>Burial</td>
</tr>
</tbody>
</table>

| **Site:** MA21 | **NO-RM** |
| **Maximum Depth [m]** | Remineralization |
| 16 | **BPC_RETURN** |
| **Atmospheric Forcing** | Sinking |
| ERA-Interim | Burial |
| **Observations** | Remineralization |
| PO4; NO3; Chl-a; NH4; O2 | **NO_RM**: Remineralization flux nullified |

| **Site:** SHB | **BPC_RETURN** |
| **Maximum Depth [m]** | Both Sinking-Burial and Remineralization fluxes were considered |
| 78 | **NO-RM**: Remineralization flux nullified |
| **Atmospheric Forcing** | **BPC_RETURN** |
| WRF model | Sinking |
| **Observations** | Burial |
| PO4; NO3; Chl-a; SiO4; O2; | Remineralization |
Study Area

- Well-mixed conditions during winter and vertical thermal stratification in summer
- Homogeneous primary production condition in winter and deep phytoplankton production in summer

Physical and Biogeochemical dynamic

- Temperature (°C) and Chlorophyll-a (μg m⁻³)

Benthic Sub-model Parameters

- Burial velocity [d⁻¹] = 0.5
- Remineralization (CNPS)[md⁻¹] = 0.0025

** Study Area figure and Chlorophyll Hovmöller from Mussap et al., 2016. Temperature monthly data from ARPA-FVG, OGS (2000-2011, 2013)
**Gulf of Trieste (MA21)**

**Seasonal Normalized (in z) Mean Bias**

- **Phosphate (mmol P/m³)**
  - JFM: NO-RM > BPC-RETURN (exception of O₂)
  - AMJ: NO-RM = BPC-RETURN
  - JAS: NO-RM > BPC-RETURN
  - OND: NO-RM = BPC-RETURN

- **Chlorophyll-a (mg Chl-a/m³)**
  - JFM: NO-RM > BPC-RETURN
  - AMJ: NO-RM = BPC-RETURN
  - JAS: NO-RM < BPC-RETURN
  - OND: NO-RM = BPC-RETURN

**Mean Seasonal Vertical Profiles**

- **Phosphate [mmol P m⁻³]**
  - JFM: NO-RM > BPC-RETURN (exception of O₂)
  - AMJ: NO-RM = BPC-RETURN
  - JAS: NO-RM > BPC-RETURN
  - OND: NO-RM = BPC-RETURN

- **Chlorophyll-a [mg Chl-a m⁻³]**
  - JFM: NO-RM > BPC-RETURN
  - AMJ: NO-RM = BPC-RETURN
  - JAS: NO-RM < BPC-RETURN
  - OND: NO-RM = BPC-RETURN

**Oxygen (mmol O₂/m³)**

- JFM: NO-RM = BPC-RETURN
- AMJ: NO-RM = BPC-RETURN
- JAS: NO-RM = BPC-RETURN
- OND: NO-RM = BPC-RETURN

- **BPC-RETURN**: Inorganic nutrients (at depth) improvements lead amelioration of the simulated Chl-a dynamic (green arrows).

---

**Key Points**:

- NMB in NO-RM > NMB in BPC-RETURN (exception of O₂)
- BPC-RETURN: Inorganic nutrients (at depth) improvements lead amelioration of the simulated Chl-a dynamic (green arrows).
- Embedded in the Benguela Current Large Marine Ecosystem
- South-easterly trade winds driven **upwelling between Sep.-Apr.** (Vertical diffusivity $[m^2 s^{-1}] = 5.0e-5$)
- Peaks of primary production occurring during the upwelling period (maxima in April and September) **Shannon et al., 1996.**

**Monthly data (2000-2017) from BENEFIT (Benguela Environment and Fisheries Interactions and Training) program of the Department of Environmental Affairs of South Africa**
Bias NO-RM > BPC-RETURN

Inorganic Nutrients seasonal improvements positively affect Chl-a dynamic seasonality (AMJ-JAS)
Cold and deep mixed dynamic
- No Sea Ice formation (Norwegian Coastal Current)
- Phytoplankton peaks in no light limited seasons.

Seasonal Normalized (in z) Mean Bias

- **Phosphate (mmol P/m^3)**
  - JFM: -0.25, AMJ: 0.00, JAS: 0.25, OND: -0.75

- **Nitrate (mmol N/m^3)**
  - JFM: -0.50, AMJ: 0.00, JAS: 0.50, OND: -1.00

- **Chlorophyll-a (mg Chl/m^3)**
  - JFM: -0.25, AMJ: 0.00, JAS: 0.25, OND: -0.75

- **Silicate (mmol Si/m^3)**
  - JFM: -0.50, AMJ: 0.00, JAS: 0.50, OND: -1.00

---

Mean Seasonal Vertical Profiles

- **Nitrate [mmol N m^{-3}]**
  - JFM: increasing, AMJ: decreasing, JAS: increasing, OND: decreasing

- **Chlorophyll-a [mg Chl-a m^{-3}]**
  - JFM: increasing, AMJ: decreasing, JAS: increasing, OND: decreasing

---

- **Bias NO-RM > BPC-RETURN**
- **No sensible Chl-a growth in winter** (light limited primary production)
- **Spring-summer nutrients consumption attributable to Phytoplankton dynamic**
**Overall goals**

1. Find the ‘best’ setup of BPC parameterizations among a range of site specific values
2. Evaluate the role of BPC in determining the pelagic biogeochemical cycling

**Analysis Procedure**

**Explore Remin and Burial ranges to find minimum error metric for PO₄, NO₃, Chla**
(Annual mean vertical profile)

Summary Diagrams
(Taylor et al., 2001, Joliff et al., 2009)

Normalized Root Mean Square Error
(Mentaschi et al., 2013)

<table>
<thead>
<tr>
<th>Site</th>
<th>Burial [m d⁻¹]</th>
<th>Remineralization [d⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA21</td>
<td>ref = 0.5</td>
<td>ref=0.0025</td>
</tr>
<tr>
<td></td>
<td>(0.35 - 0.65)</td>
<td>(0.00175-0.00325)</td>
</tr>
<tr>
<td>SHB</td>
<td>ref=1.0</td>
<td>ref=(0.0025)</td>
</tr>
<tr>
<td></td>
<td>(0.60 - 1.20)</td>
<td>(0.00175-0.00325)</td>
</tr>
<tr>
<td>SFyr</td>
<td>ref=1.0</td>
<td>ref=(0.0050)</td>
</tr>
<tr>
<td></td>
<td>(0.10 - 1.50)</td>
<td>0.00350-0.00800</td>
</tr>
</tbody>
</table>
Outcomes of Sensitivity Analysis

**Summary Diagrams**

- **Identification of best model setup from FG**
  - MA21
  - SHB
  - SFyr

- **Effect of BPC processes on pelagic dynamics**
  - MA21 and SFyr: small variations of inorganic nutrients affect primary production
  - SHB: Nutrients variation does not affect primary production dynamic

**NRMSE**

Max NRMSE spread (Worse – Best) Experiment:

- PO4
- NO3
- CHL
- ErrCum

Remineralization-grouped
**Final setup of BPC parameters**

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth [m]</th>
<th>Bur [m d$^{-1}$]</th>
<th>Remin [d$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA21</td>
<td>16</td>
<td>0.35</td>
<td>0.00 325</td>
</tr>
<tr>
<td>SHB</td>
<td>78</td>
<td>0.60</td>
<td>0.00 175</td>
</tr>
<tr>
<td>SFyr</td>
<td>150</td>
<td>0.10</td>
<td>0.00 800</td>
</tr>
</tbody>
</table>

**Estimate of benthic-pelagic fluxes**

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth [m]</th>
<th>POC-Burial [mg C m$^{-2}$ d$^{-1}$]</th>
<th>N-Remin [mmol N m$^{-3}$ d$^{-1}$]</th>
<th>P-Remin [mmol p m$^{-3}$ d$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA21</td>
<td>16</td>
<td>-0.1344</td>
<td>0.910</td>
<td>0.050</td>
</tr>
<tr>
<td>SHB</td>
<td>78</td>
<td>-0.0021</td>
<td>1.027</td>
<td>0.068</td>
</tr>
<tr>
<td>SFyr</td>
<td>150</td>
<td>-0.0636</td>
<td>0.336</td>
<td>0.016</td>
</tr>
</tbody>
</table>

- **Dependency** between station **depth** and BP fluxes intensity
  
  [Suess et al., 1980]

**Qualitative analysis NRMSE based**

**Initial setup of BPC parameters (First Guess)**

**Final setup of BPC parameters (Best Exp.)**

- SHB, SFyr widespread improvements
- MA21 improvements with exception of PO4
Results: Best Experiments

MA21

PO4

NO3

Chla

O2

NH4

SHB

PO4

NO3

Chla

O2

SIL

SFyr

PO4

NO3

Chla

SIL

JFM AMJ JAS OND
The benthic-pelagic dynamic processes were successfully implemented for the three different sites;

The intercomparison between the BPC-RETURN and the NO-RM experiment allowed to assess the model improvements in reproducing B-P fluxes;

The extensive sensitivity analysis showed different sedimentation-remineralization scenarios where the shallower sites were more sensitive to the BPC parameterization.

MA21 and SHB areas were characterized by a more active benthic nutrients regeneration while SFyr and MA21 were characterized by the highest rates of deposition.

The agreement between the used pattern statistics successfully allowed to individuate the Best Experiments (Final setup).
Thank you
Supplementary slides
BPC Implementation
(NO-RM vs BPC_RETURN exps)
NO-RM vs BPC_RETURN

Results

MA21

SHB

SFyr
Sensitivity Analysis Scheme
Sensitivity Experiment Matrix

Mean NRMSE (all variables)

Mean NRMSE (Sensitivity analysis variables)
Sensitivity Analysis
Best Exp Identification
MA21: Identification of “Best Experiment”

Clouds of experiments grouped by Remineralization sets

Best Exp: Remin +10%

Best Exp: Remin +30%

Best Exp: Remin +30%
SHB Identification of “Best Experiment”

Clouds of experiments grouped by Remineralization sets

**Best Exp: Remin -30%**

**Best Exp: Remin -25/-30%**

**Best Exp: Remin -30%**
SHB Identification of “Best Experiment”

Best Exp: Remin - 30%

Best Exp: Remin - 30%

Best Exp: Remin -25/- 30%

Clouds of experiments grouped by:
Remineralization sets

-25%
-30%
Identification of “Best Experiment”

Clouds of experiments grouped by Remineralization sets

Best Exp: Remin
+60%

Best Exp: Remin
+60%

Best Exp: Remin
+60%
Agreement between used pattern statistics

SHB

<table>
<thead>
<tr>
<th>Variable</th>
<th>RMSD</th>
<th>Taylor diagram</th>
<th>Target diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate</td>
<td>B -30% R -30%</td>
<td>R -30%</td>
<td>R -30%</td>
</tr>
<tr>
<td>Nitrate</td>
<td>B -10% R -25%</td>
<td>R -30%</td>
<td>R -30% / R -25%</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>B +20% R -30%</td>
<td>R -30%</td>
<td>R -30%</td>
</tr>
<tr>
<td>Avg RMSD</td>
<td>B -40% R -30%</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

SFyr

<table>
<thead>
<tr>
<th>Variable</th>
<th>RMSD</th>
<th>Taylor diagram</th>
<th>Target diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate</td>
<td>B -90% R +60%</td>
<td>not clear</td>
<td>R +60%</td>
</tr>
<tr>
<td>Nitrate</td>
<td>B -90% R +60%</td>
<td>not clear</td>
<td>R +60%</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>B -90% R +60%</td>
<td>R +60%</td>
<td>R +60%</td>
</tr>
<tr>
<td>Avg RMSD</td>
<td>B -90% R +60%</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

MA21

<table>
<thead>
<tr>
<th>Variable</th>
<th>NRMSD</th>
<th>Taylor diagram</th>
<th>Target diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate</td>
<td>B -30% R -10%</td>
<td>R -30%</td>
<td>R -10%</td>
</tr>
<tr>
<td>Nitrate</td>
<td>B -30% R +30%</td>
<td>R +30%</td>
<td>R +30%</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>B -30% R +30%</td>
<td>R -30% / R -20%</td>
<td>R +30%</td>
</tr>
<tr>
<td>Avg RMSD</td>
<td>B -30% R +30%</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Sensitivity Analysis
Best Exp Vertical Profiles
Mean Absolute Error (MAE)

**Best Guess-Obs vs First Guess-Obs**

### MA21

- **JFM**
  - Nitrate [mmol N m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Oxygen [mmol O\(_2\) m\(^{-3}\)]

- **AMJ**
  - Nitrate [mmol N m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Oxygen [mmol O\(_2\) m\(^{-3}\)]

- **JAS**
  - Nitrate [mmol N m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Oxygen [mmol O\(_2\) m\(^{-3}\)]

- **OND**
  - Nitrate [mmol N m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Oxygen [mmol O\(_2\) m\(^{-3}\)]

### SHB

- **JFM**
  - Phosphate [mmol P m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Silicate [mmol Si m\(^{-3}\)]

- **AMJ**
  - Phosphate [mmol P m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Silicate [mmol Si m\(^{-3}\)]

- **JAS**
  - Phosphate [mmol P m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Silicate [mmol Si m\(^{-3}\)]

- **OND**
  - Phosphate [mmol P m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Silicate [mmol Si m\(^{-3}\)]

### SFyr

- **JFM**
  - Nitrate [mmol N m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Silicate [mmol Si m\(^{-3}\)]

- **AMJ**
  - Nitrate [mmol N m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Silicate [mmol Si m\(^{-3}\)]

- **JAS**
  - Nitrate [mmol N m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Silicate [mmol Si m\(^{-3}\)]

- **OND**
  - Nitrate [mmol N m\(^{-3}\)]
  - Chlorophyll-a [mg Chla m\(^{-3}\)]
  - Silicate [mmol Si m\(^{-3}\)]