Variability of the Black Sea hydrodynamics and biogeochemistry system.

Arthur Capet; IMEDEA April 2014
Study of the multi-decadal evolution of the **Black Sea** hydrodynamics and biogeochemistry using mathematical modelling
Study of the multi-decadal evolution of the **Black Sea** hydrodynamics and biogeochemistry using mathematical modelling

Enviromental resources: marine Goods and Services
Study of the multi-decadal evolution of the Black Sea hydrodynamics and biogeochemistry using mathematical modelling

The capacity to deliver Goods and Services depend on Environmental status

Goods and Services
- Fisheries
- Biodiversity
- Tourism
- Carbon sequestration
- ...

Environmental status
Study of the multi-decadal evolution of the Black Sea **hydrodynamics** and biogeochemistry using mathematical modelling

**Physics**

Circulation and mixing of water masses.

### Goods and Services
- Fisheries
- Biodiversity
- Tourism
- Carbon sequestration
- ...

### Environmental status
- **Hydrodynamics**

**Chemistry and Biology**

Cycles of the basic elements of life:

- Carbon, Nitrogen, Oxygen, Phosphorus, Silicate

Transport and transformation

- Inorganic (nutrients)
- Living (planktons)
- Detrital (dead cells, faeces)

**Goods and Services**

- Fisheries
- Biodiversity
- Tourism
- Carbon sequestration
- ...

**Environmental status**

- Hydrodynamics
- Biogeochemistry
Study of the **multi-decadal evolution** of the Black Sea hydrodynamics and biogeochemistry using mathematical modelling

Dynamic system

→ Physical and biogeochemical characteristics are **variables** in **Space** and **Time**

**Multi-decadal**: from 1960 to present

**External forcings:**
- Atmospheric conditions
- Riverine inputs

**Goods and Services**
- Fisheries
- Biodiversity
- Tourism
- Carbon sequestration
- ...

**Environmental status**
- Hydrodynamics
- Biogeochemistry
Study of the **multi-decadal evolution** of the Black Sea hydrodynamics and biogeochemistry using mathematical modelling

**Pressure on Ecosystem**
- Climate change
- Eutrophication
- Invasive species
- Fishing Pressure
- Benthic habitat destruction
- ...

**Goods and Services**
- Fisheries
- Biodiversity
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- ...

**Environmental status**
- Hydrodynamics
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- Fisheries
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- Carbon sequestration
- ...

**Environmental status**
- Hydrodynamics
- Biogeochemistry

**My Work**
Study of the multi-decadal evolution of the Black Sea hydrodynamics and biogeochemistry using **mathematical modelling**

A computer software to reproduce the dynamics of the Black Sea ecosystem

3D mechanistic model

My Work
Study of the multi-decadal evolution of the Black Sea hydrodynamics and biogeochemistry using **mathematical modelling**

- **Pressure on Ecosystem**
  - Climate change
  - Eutrophication
  - Invasive species
  - Fishing Pressure
  - Benthic habitat destruction
  - ...

- **Goods and Services**
  - Fisheries
  - Biodiversity
  - Tourism
  - Carbon sequestration
  - ...

- **Environmental status**
  - Hydrodynamics
  - Biogeochemistry
Study of the multi-decadal evolution of the Black Sea hydrodynamics and biogeochemistry using **mathematical modelling**

**Pressure on Ecosystem**
- Climate change
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- ...

**Goods and Services**
- Fisheries
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- ...

**Environmental status**
- Hydrodynamics
- Biogeochemistry

**Management tools & Environmental Policies**
Outline

Hydrodynamics

- Introduction: The Black Sea structure
  - Variability from observations: describe
  - Variability from model: resolve and explain

Biogeochemistry

- Introduction: Hypoxia in the Northwestern shelf
  - Model requirements
  - Dynamics of hypoxia
Outline

**Hydrodynamics**
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A quasi enclosed basin
The Bosphorus Strait
A large drainage area

→ Large riverine inputs: fresh water and nutrients
A large drainage area

→ Large riverine inputs: fresh water and nutrients

Northwestern Shelf
- Shallow (<120 m)
- Rich in nutrients
- Rich ecosystem
A large drainage area

→ Large riverine inputs: fresh water and nutrients
A large drainage area

→ Large riverine inputs: fresh water and nutrients
A large drainage area

→ Large riverine inputs: fresh water and nutrients

Northwestern Shelf
- Shallow
- Rich in nutrients
- High biodiversity

Central basin
- Deep (>2000m)
- Poor in nutrients
Circulation

The Rim Current
Circulation

Riverine inputs
350 km³/yr
Salinity ~ 0
Circulation

Riverine inputs
350 km³/yr
Salinity ~ 0
Circulation

Surface Outflow
600 km³/yr
Salinity ~ 18

Bottom Inflow
300 km³/yr
Salinity ~ 32
Vertical structure

Salinity [psu]
Vertical structure

Halocline

Salinity [psu]

Density [kg/m³]

Stratification [/s]

(Brunn Vaiasala frequency)
Vertical structure

- **Thermocline**
- **Halocline**
- **Salinity [psu]**
- **Density [kg/m³]**
- **Stratification [/s]**

**WINTER**

**SUMMER**
Vertical structure

Dense water formation

Convective sinking blocked by the Halocline

Cold Intermediate Layer

Thermocline

Halocline

Temperature [°C]
Vertical structure

→ No mixing between surface and deep waters.
→ No oxygen below 200 m
Vertical structure

→ No mixing between surface and deep waters.
→ No oxygen below 200 m

Small active volume
+ Large influence Area
= Sensitivity to changing external forcings
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(Capet et al. 2014, Ocean Dynamics)
Vertical profiles → Diagnostics

Mixed Layer Depth

Cold Intermediate layer
cold content

(Capet et al. 2014, Ocean Dynamics)
Vertical profiles → Diagnostics → Spatial variability

Mixed Layer Depth

(Capet et al. 2014, Ocean Dynamics)
Vertical profiles → Diagnostics → Spatial variability

(Capet et al. 2014, Ocean Dynamics)
The uneven distribution of data alters the apparent variability.

(Capet et al. 2014, Ocean Dynamics)
Vertical profiles → Diagnostics → Spatial variability

DIVA detrending analysis
Correct the bias induced by uneven distribution

(Capet et al. 2014, Ocean Dynamics)
Vertical profiles → Diagnostics → Spatial variability

DIVA detrending analysis
Correct the bias induced by uneven distribution
→ Monthly climatologies of MLD and CCC

(Capet et al. 2014, Ocean Dynamics)
Temporal variability

Inter-annual

Seasonal

(Capet et al. 2014, Ocean Dynamics)
Temporal variability

Explained by the anomaly of winter air temperature cumulated over the 4 past years

(Capet et al. 2014, Ocean Dynamics)
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Biogeochemistry
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To build a hydrodynamic model you need ...

- Domain: Bathymetry, open boundaries.
- State variables: Temp., Sal., Currents, Elevation, Internal turbulence
- Hydrodynamic equations
- External forcings: River flows, Atmospheric conditions
Model experiment

**Objective**: Relate the variability of the Black Sea structure to the variability of atmospheric conditions

Long term simulation with realistic forcings: 1960-2000

(Capet et al. 2012, Deep-Sea Research II)
Model Diagnostics

- Surface
  - Sea surface temperature (SST)
- Water column
  - Mixed layer depth (MLD)
  - Cold intermediate layer Cold content (CCC)
  - Mean kinetic energy (MKE)

(Capet et al. 2012, Deep-Sea Research II)
Model Diagnostics

- **Surface**
  - Sea surface temperature (SST) **Satellite**

- **Water column**
  - Mixed layer depth (MLD)
  - Cold intermediate layer Cold content (CCC)
  - Mean kinetic energy (MKE)

(Capet et al. 2012, Deep-Sea Research II)
Interannual Anomalies

40 years Signal = Seasonal Variability + Interannual Anomalies

(Capet et al. 2012, Deep-Sea Research II)
Interannual Anomalies

40 years Signal = Seasonal Variability + Interannual Anomalies

(Capet et al. 2012, Deep-Sea Research II)
Sea Surface Temperature anomalies


(Capet et al. 2012, Deep-Sea Research II)
The model allows to go back in time

Satellite era

Surface Temp.

(Capet et al. 2012, Deep-Sea Research II)
SST respond to large teleconnection patterns with various temporal scales

(Capet et al. 2012, Deep-Sea Research II)
The model allows to go underwater

(Capet et al. 2012, Deep-Sea Research II)
CIL cold content: Model VS Profiles

Vertical profiles (DIVA detrending)

(Model)

(Capet et al. 2012, Deep-Sea Research II)
The model allows to go underwater

Surface Temp.

Mixed Layer Depth

CIL cold content

(Capet et al. 2012, Deep-Sea Research II)
Rim Current intensity

Kinetic energy

(Capet et al. 2012, Deep-Sea Research II)
Rim Current intensity

Kinetic energy

(Capet et al. 2012, Deep-Sea Research II)
Atmospheric regimes

38 years = 468 monthly anomalies classified in 6 patterns (Self Organizing Maps analysis)

(Capet et al. 2012, Deep-Sea Research II)
Rim current & winds regime

Cyclonic patterns

Anti-Cyclonic patterns

(Capet et al. 2012, Deep-Sea Research II)
Negative curls patterns with border of the same colors than bars...

Cyclonic patterns

Anti-Cyclonic patterns

Rim current & winds regime

(Capet et al. 2012, Deep-Sea Research II)
Rim current & winds regime

Cyclonic patterns

Anti-Cyclonic patterns

(Capet et al. 2012, Deep-Sea Research II)
Rim current & winds regime

How times the patterns appears in a two year?

(Capet et al. 2012, Deep-Sea Research II)
Rim current & winds regime

Longer persistence of anomalous patterns

Black Sea system further from equilibrium.

(Capet et al. 2012, Deep-Sea Research II)
Conclusions (Hydrodynamics) -1/3

- The 3D model reproduces the variability of hydrodynamics with accuracy.
  - Surface variability validated with satellite data.
  - Internal variability validated with vertical profiles.
Conclusions (Hydrodynamics) - 2/3

- The Rim current intensity regulates the sensitivity of the Black Sea structure to air temperature.
Conclusions (Hydrodynamics) - 3/3

- The longer persistence of atmospheric anomalies brought the System further from its average state
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(Capet et al. 2013, Biogeosciences)
What is hypoxia?

Hypoxic threshold: $[O_2] < 62 \text{ mmol/m}^3 (2 \text{ mg/l})$
Why does hypoxia occur?
Deep basin: permanent anoxia below 
~150/200 m

(Capet et al. 2013, Biogeosciences)
Seasonal Hypoxia

Hypoxic threshold: $[O_2] < 62 \text{ mmol/m}^3$ (2 mg/l)

(Capet et al. 2013, Biogeosciences)
Seasonal Hypoxia

Phytoplankton growth

Respiration

Hypoxic threshold: \([O_2] < 62 \text{ mmol/m}^3 (2 \text{ mg/l})\)

(Capet et al. 2013, Biogeosciences)
Seasonal Hypoxia in the BS-NWS

(Capet et al. 2013, Biogeosciences)
Recovery?

1980-1987

1988-1995

1996-2002

2003-2009

Oxygen records
(World ocean atlas, Seadatanet, Black Sea Commission data)

Hypoxic records
(<62 mmol O/m³)

(Capet et al. 2013, Biogeosciences)
Studying Hypoxia with a 3D model

(Capet et al. 2013, Biogeosciences)
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(Capet et al. 2013, Biogeosciences)
To build a biogeochemical model you need...

River inputs (freshwater)

Atmospheric model & data
To build a biogeochemical model you need...

River inputs (freshwater)

Atmospheric model & data

Surface fluxes (heat, momentum, freshwater)

Hydrodynamics → Currents, mixing, Temp., Sal.

(Capet et al. 2013, Biogeosciences)
To build a biogeochemical model you need...

- River inputs (nutrients, freshwater, suspended matter)
- Surface fluxes (heat, momentum, nutrients, oxygen, freshwater)
- Hydrodynamics → Currents, mixing, Temp., Sal.
- 36 state variables
- C, N, P, Si, O
- 3 phyto. Groups
- 4 zoo groups.

(Capet et al. 2013, Biogeosciences)
To build a biogeochemical model you need...

River inputs (nutrients, freshwater, suspended matter)

Surface fluxes (heat, momentum, nutrients, oxygen, freshwater)

Hydrodynamics → Currents, mixing, Temp., Sal.

36 state variables

3 phyto. Groups
4 zoo groups.

C, N, P, Si, O

Photosynthesis, Bacterial loop, Chemistry, ...

Atmospheric model & data

Anoxic Chemistry

(Capet et al. 2013, Biogeosciences)
36 State variables

(Capet et al. 2013, Biogeosciences)
To build a biogeochemical model you need...

River inputs (nutrients, freshwater, suspended matter)

Surface fluxes (heat, momentum, nutrients, oxygen, freshwater)

Hydrodynamics → Currents, mixing, Temp., Sal.

C, N, P, Si, O

Photosynthesis, Bacterial loop, Chemistry, ...

Organic matter deposition.
Resuspension by waves and bottom stress.
Benthic diagenesis → Diffusive fluxes.

(Stanev and Kandilarov, 2012; Soetart, 2000)
(Capet et al. 2013, Biogeosciences)
Biogeochemical role of the sediment layer

Region 1 (25 km² / 15-57 m)
Avg. Dc: 9 molC/m²/yr
Oxic: 17%
Denit.: 8%
Anox.: 75%

Region 2 (30.2 km² / 23-95 m)
Avg. Dc: 4 molC/m²/yr
Oxic: 34%
Denit.: 11%
Anox.: 55%

Region 3 (23.2 km² / 46-120 m)
Avg. Dc: 2 molC/m²/yr
Oxic: 52%
Denit.: 9%
Anox.: 39%
Biogeochemical role of the sediment layer
Outline

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  • Model requirements
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(Capet et al. 2013, Biogeosciences)
Model validation

Does the model adequately resolves ...

- the horizontal distribution
- the seasonal distribution
- the interannual distribution
- the vertical distribution
- the specific occurrence of hypoxia

... reflected by in situ observations?

(Capet et al. 2013, Biogeosciences)
Model validation

Does the model adequately resolve ...
  the horizontal distribution
  the seasonal distribution
  the interannual distribution
  the vertical distribution
  the specific occurrence of hypoxia

... reflected by in situ observations?

Yes, yes, yes, yes, yes and yes

(Capet et al. 2013, Biogeosciences)
Model Validation: Point-to-point

Merged by months → validation of the seasonal cycle

Hypoxic records - [%]  
(<62 mmol O/m³)

\([O_2] - [\text{mmol/m}^3]\)

(Capet et al. 2013, Biogeosciences)
Interannual Model-Data comparison

[Graph showing comparison of model and observations over the years 1980 to 2010. The x-axis represents years, and the y-axis represents oxygen concentration in mmol/m³. The graph compares observations (red dots) and model outputs (blue dots).]

(Capet et al. 2013, Biogeosciences)
Interannual Model-Data comparison

\[ [O_2] - [\text{mmol/m}^3] \]

(Capet et al. 2013, Biogeosciences)
Interannual Model-Data comparison

[O₂] – [mmol/m³]

1980-1987

1988-1995

1996-2002

2003-2009

(Capet et al. 2013, Biogeosciences)
Interannual variability
The H-index

An Index to quantify the intensity of hypoxia as an environmental pressure on ecosystems

The H-index express the spatial extension of hypoxia..

.. modulated by the duration of hypoxia

(Capet et al. 2013, Biogeosciences)
Interannual variability of Hypoxia

(Capet et al. 2013, Biogeosciences)
Interannual variability of Hypoxia

What are the drivers of this interannual variability?

(Capet et al. 2013, Biogeosciences)
Interannual variability of Hypoxia

Eutrophication and climate

(1) High nitrogen riverine discharge.
(2) High sedimentary organic carbon content.

(3) Warm springs.
(4) Warm summers.

36 %
27 %
82 %

(Capet et al. 2013, Biogeosciences)
Can we exploit this knowledge for management purposes?
Hypoxia response to N discharge

Includes the year specific influences of climatic and sediments drivers

(Capet et al. 2013, Biogeosciences)
Hypoxia response to N discharge

Response curve for average atmospheric conditions (1980-2009)

(Capet et al. 2013, Biogeosciences)
These average atmospheric conditions are not valid anymore.
Hypoxia response to N discharge

Area affected by hypoxia [10^3 km^2]

Nitrogen discharge by the rivers - [Gmol N /yr]

- Past years (1981-2009)
- 1981-2009
- 2015-2020

?
The cost of warming

- Hypoxia vs. Nitrogen loads

- Graph showing the relationship between hypoxia and nitrogen loads.
The cost of warming

Current Nitrogen loads

Environmental cost 20 % increase of Hypoxia

(= +3% of the shelf area)
The cost of warming

Current Hypoxia level

Economical cost
24 % reduction of nutrient loads

Nitrogen loads
Conclusion (Hypoxia)
Conclusion (Hypoxia) – 1/3

Hypoxia is still ongoing in the Black Sea NWS

Monitoring should be focused on the area, months and depth of known hypoxia occurrence.
Conclusions (Hypoxia) – 2/3

Hypoxia is intensified by year-to-year accumulation of organic matter in the sediments

Systems with decreasing N → Inertia in the recovery process

Systems with increasing N → Increase of the H/N ratio
Conclusion (Hypoxia) – 3/3

Climate impacts almost as much as eutrophication.

Nutrient reduction policies must account for realistic climatic scenarios.
General Conclusions

- The **physical model** reproduces the **variability of the Black Sea internal structure** and allows to investigate its **sensitivity to atmospheric conditions**

- The **biogeochemical model** allowed us to untangle the **complex dynamics of hypoxia** and to evidence the **specific impact of its main drivers**
General Conclusions

- 3D biogeochemical models are essential to understand to complex dynamics of marine ecosystems, in which physical, chemical and biological processes are intimately interconnected.

- As such these models are indispensable to allow a sustainable management of the goods and services provided by marine ecosystems and to assess to which extent these are endangered by the synergistic impacts of environmental pressures.
Thank you for your attention
... and questions!
SST anomalies
SST-2

CCC-2

r=0.54
T and S profiles: Central Basin
Sea surface temperature anomaly [$^\circ$C] vs Air temperature anomaly [$^\circ$C]

- **High RIM**: 0.55 $^\circ$C/$^\circ$C, $r^2$: 0.75
- **Low RIM**: 0.74 $^\circ$C/$^\circ$C, $r^2$: 0.67
Nitracline in the open basin
Role of the sediments layer in biogeochemical budgets on the shelf

Region 1 (25 km² / 15-57 m)
Avg. Dc: 9 molC/m²/yr
Oxic: 17%
Denit.: 8%
Anox.: 75%

Region 2 (30.2 km² / 23-95 m)
Avg. Dc: 4 molC/m²/yr
Oxic: 34%
Denit.: 11%
Anox.: 55%

Region 3 (23.2 km² / 46-120 m)
Avg. Dc: 2 molC/m²/yr
Oxic: 52%
Denit.: 9%
Anox.: 39%

Oxygen: 375 Gmol/yr
Nitrogen: 29 Gmol/yr
Carbon: 43 Gmol/yr
Deposition Interval

Time during which bottom stress is generally lower than the resuspension threshold
Benthic environmental conditions
Validation in the Open basin: Oxygen, Nitrate
Validation in the Open basin: Oxygen Temporal

Oxygen

![Graphs showing oxygen temporal data over different months and years.]
Interannual variability of Hypoxia

1. High nitrogen riverine discharge enhance the influx of organic matter to bottom waters.
2. High sedimentary organic carbon content enhances the benthic oxygen consumption.
3. Warm springs reduce the ventilation and set summer bottom temperature.
4. Warm summers extend the duration of the stratified period.

Oxygen exchange with Atmosphere

Depth [m]

Living Time

0 5 10 15 20

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Oxygen Consumption
Model Validation: Point-to-point

a) Observations

b) Predictions

[Graph showing a scatter plot with depth vs. bottom depth, with color coding for [mmol O₂/m³]]
\[ D = \frac{1}{\max A(t)} \int_{year} A(t) \, dt, \]

\[ H = \frac{1}{D} \int_{year} A(t) \, dt, \]
\[ D = \frac{1}{\max A(t)} \int_{\text{year}} A(t) \, dt, \quad H = \frac{1}{D} \int_{\text{year}} A(t) \, dt, \]

\[ \text{H index} - [10^3 \text{ km}^2] \]

\[ \text{maximal hypoxic area} - [10^3 \text{ km}^2] \]

\[ \text{duration of hypoxia} - [\text{d}] \]
Recovery?

1980-1987
1988-1995
1996-2002
2003-2009

5826
7647
981
339

<2mg/l:
50
127
0
0

Hypoxic areas - [10^3 km²]

Mee 2006
present study
UkrSCES 2002

Recovery?

- 1980-1987: 5826, <2 mg/l: 50
- 1996-2002: 981, 0
- 2003-2009: 339, 0

(a) Hypoxic areas - [10^3 km^2]
(b) Data sources:
- Yellow: Mee 2006
- Blue: Present study
- Red: UkrSCES 2002

Yearly data from 1980 to 2010.
Benthic Model

Resuspension
in particulate form
due to bottom stress from **currents** and (mainly) **waves**.

Remineralised content (in mmolC/m²/s)
\[
= [\text{fast C stock}] \cdot K_{fc} \cdot f(T°) \\
+ [\text{slow C stock}] \cdot K_{sc} \cdot f(T°)
\]

Calibrated functions compute from Cmin and Nmin, the fluxes of **Oxygen**, **ODU**, **DIC**, **Ammonium**, **Nitrate**, **Silicate**, according to benthic conditions.

**Benthic remineralisation**

\( W_{\text{POC}} \) is given by aggregation model

**sedimenting variables**
(POM, Diatoms)

2D Sed. Variables

<table>
<thead>
<tr>
<th>Fast remin. C stock</th>
<th>Slow remin</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/C ratio</td>
<td></td>
</tr>
</tbody>
</table>

Slow remin. S Stock

Fast remin.
Application : dynamique de l'hypoxie sur le plateau continental Nord Ouest

![Graphs showing oxygen concentrations during mixing and stratification periods.](image-url)
Circulation: impact sur la structure verticale

- JAN
- FEB
- MAR
- APR
- MAY
- JUN
- JUL
- AUG
- SEP
- OCT
- NOV
- DEC

Oxycline Depth - [m]
Circulation

Surface fresh waters

Deep salted waters
The figure shows a line graph with time on the x-axis, ranging from 1980 to 2010, and a variable H expressed in $10^3$ km$^2$ on the y-axis, ranging from 0 to 25.

The graph includes two line plots:
- The blue dotted line represents a 3D model.
- The red dotted line represents a regression model: $H = a_0 + a_N N^* + a_C C^* + a_{T_s} T_s^* + a_{T_f} T_f^*$.

In the upper right corner, the explained variance ($R^2$) is given as 82%.

The inset chart displays the explained variance for different parameters: $a_N$, $a_C$, $a_{T_s}$, and $a_{T_f}$, with values for $36\%$ and $27\%$ respectively.
The case of Hypoxia
Organic matter accumulates in the sediments

\[ C(y + 1) = C(y)(1 - \beta(y)) + \alpha(y) \cdot N(y) \]  \hspace{1cm} (8)

\[ \beta(y) = \beta_0 \cdot Q_{T_s}^{*}(y) \]  \hspace{1cm} (9)

\[ \alpha(y) = \alpha_0 + \alpha_{\text{Si:N}} \cdot (\text{Si}(y) : N(y)) \]  \hspace{1cm} (10)
Next? : End-to-end modeling!