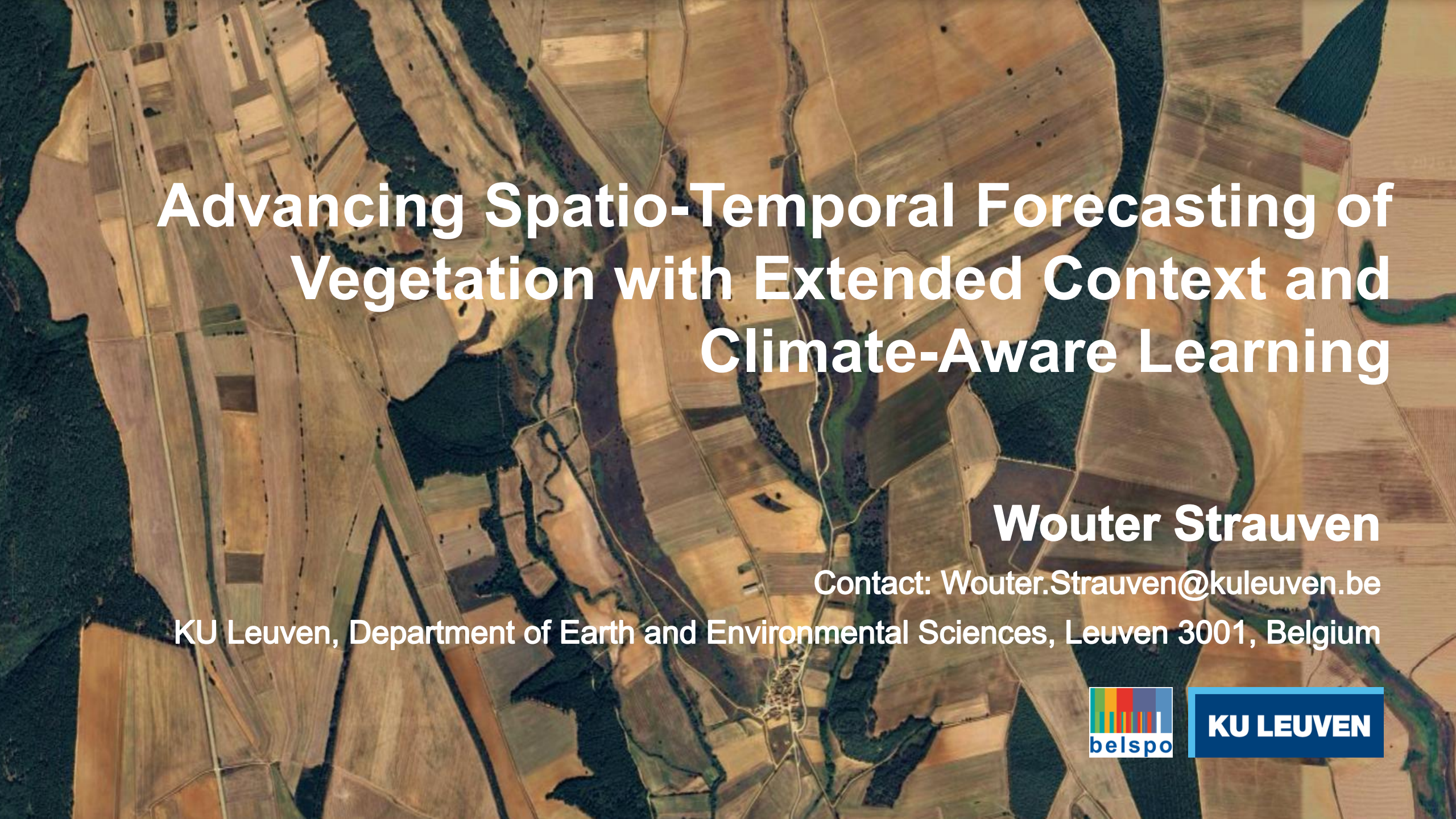


Advancing Spatio-Temporal Forecasting of Vegetation with Extended Context and Climate-Aware Learning

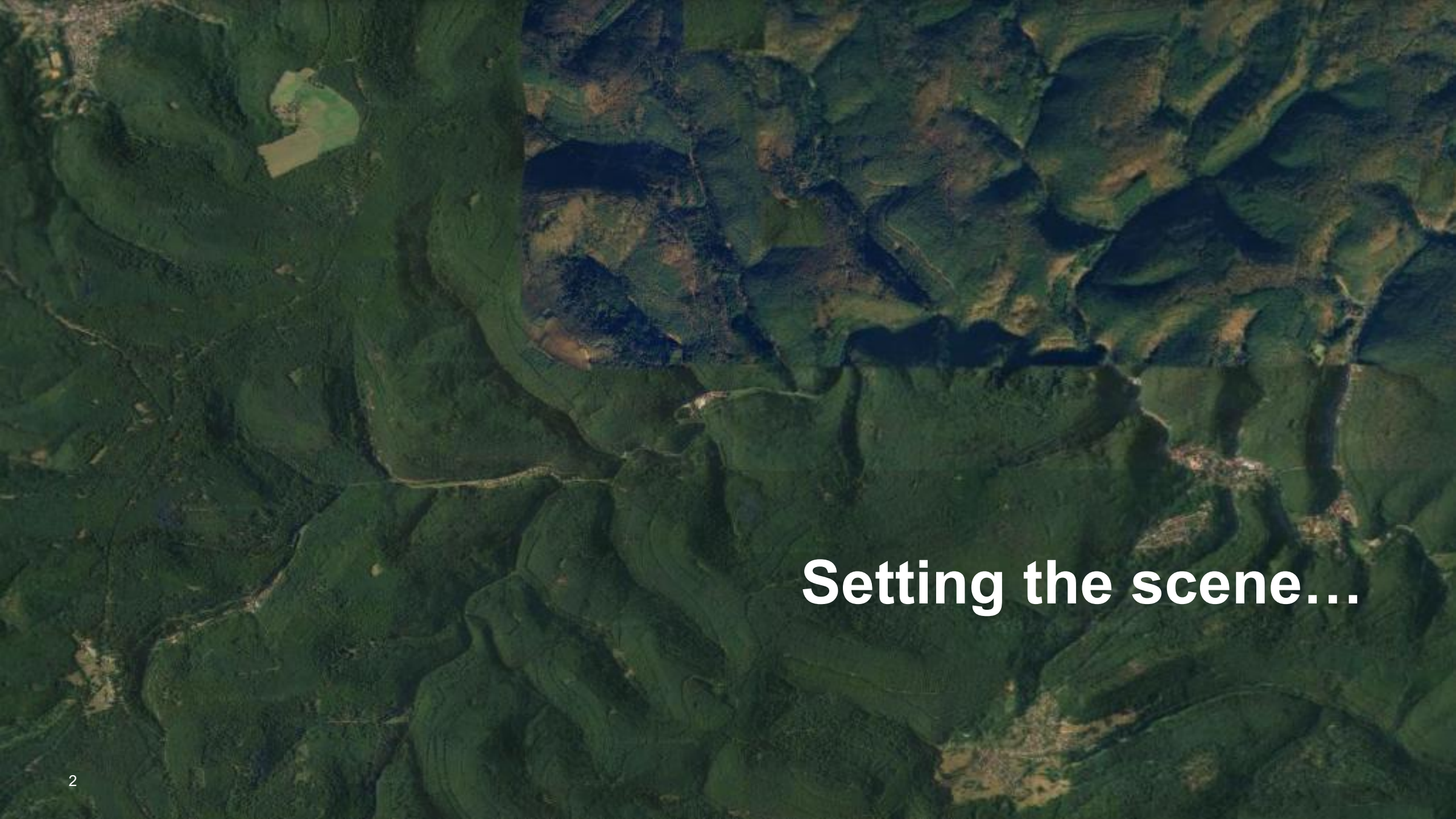
Wouter Strauven

Contact: Wouter.Strauven@kuleuven.be

KU Leuven, Department of Earth and Environmental Sciences, Leuven 3001, Belgium

belspo

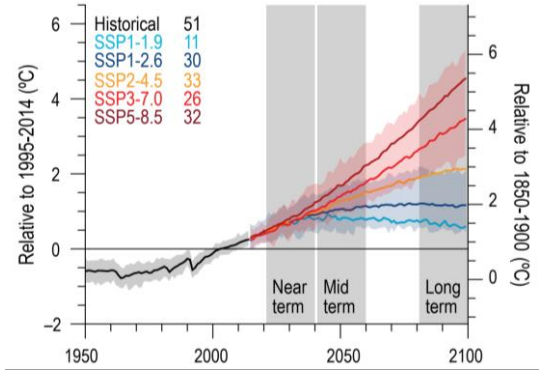
KU LEUVEN


Setting the scene…

Past

Present

Future

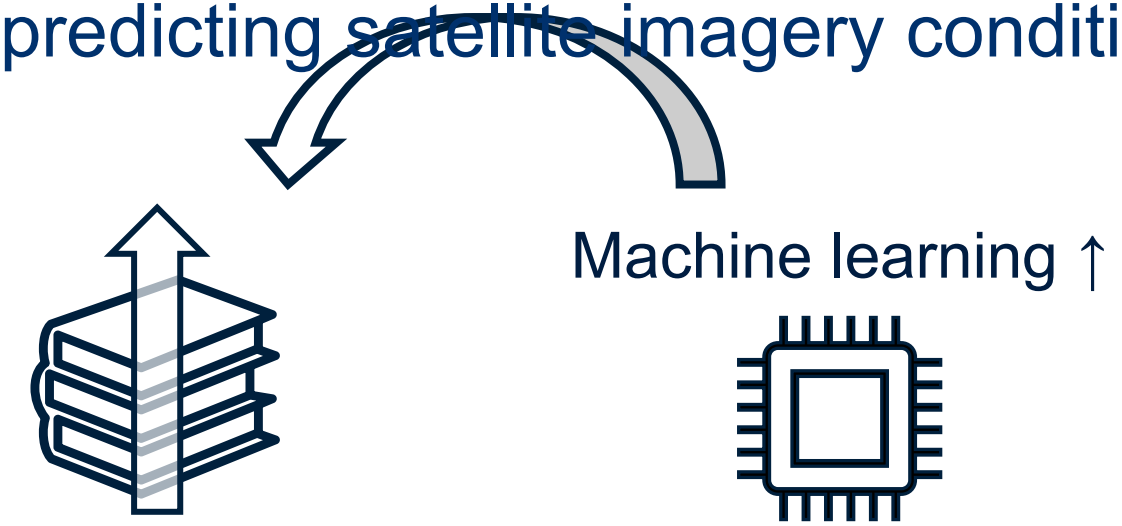


Lee et al., 2021

Earth Surface Forecasting

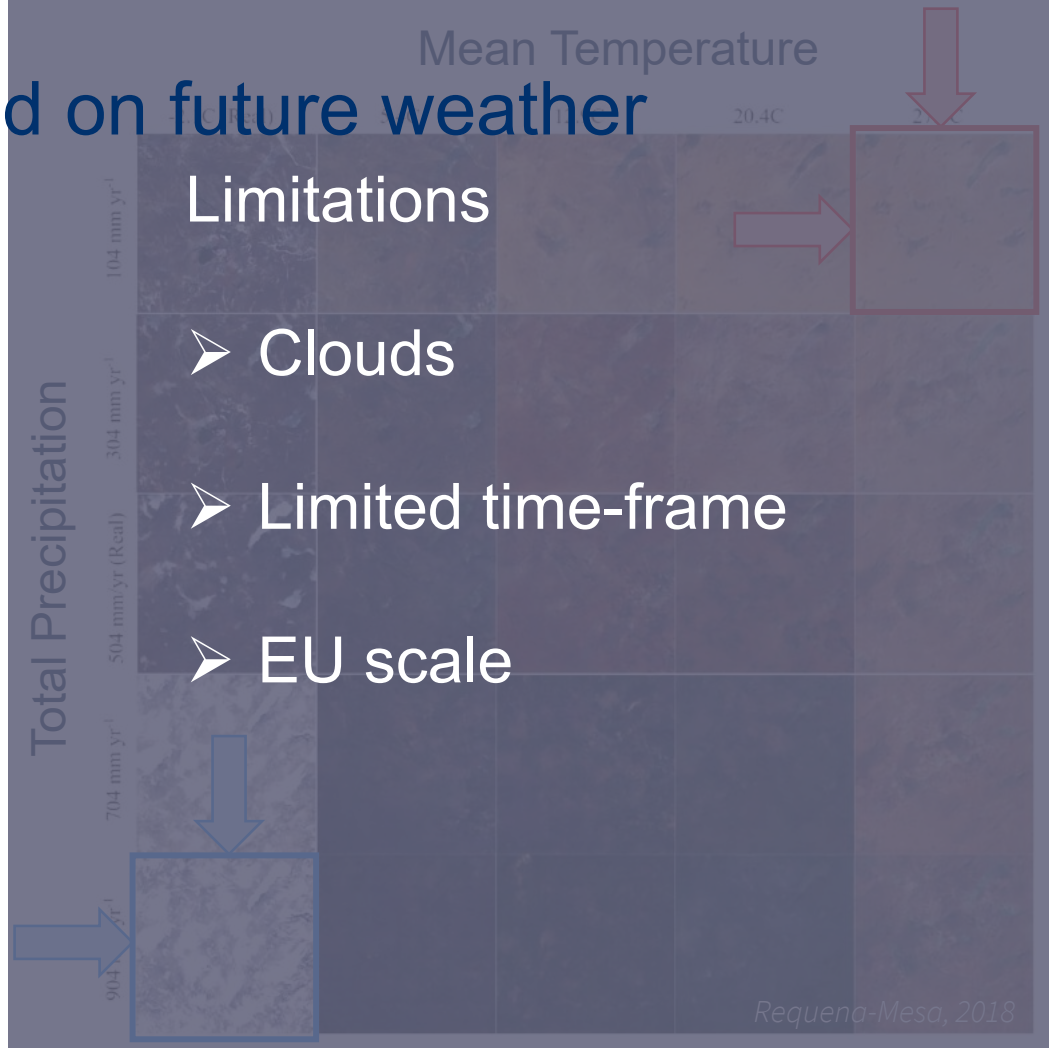
Earth Surface Forecasting

= predicting satellite imagery conditioned on future weather



EarthNet2021: A large-scale dataset and challenge for Earth surface forecasting as a guided video prediction task.

Christian Requena-Mesa[1,2,3,*], Vitus Benson[1,*], Markus Reichstein[1,4], Jakob Runge[2,5], Joachim Denzler[2,3,4]



Limitations

- Clouds
- Limited time-frame
- EU scale

Geospatial Vegetation Forecasting

Multi-modal learning for geospatial vegetation forecasting

Vitus Benson[1,2,3,*] Claire Robin[1,2] Christian Requena-Mesa[1,2] Lazaro Alonso[1]
Nuno Carvalhais[1,2] José Cortés[1] Zhihan Gao[4] Nora Linscheid[1] Mélanie Weynants[1]
Markus Reichstein[1,2]
[1] Max-Planck-Institute for Biogeochemistry [2] ELLIS Unit Jena [3] ETH Zürich
[4] Hong Kong University of Science and Technology [*] vbenson@bgc-jena.mpg.de

Limitations

- **Limited time-frame**
- EU scale

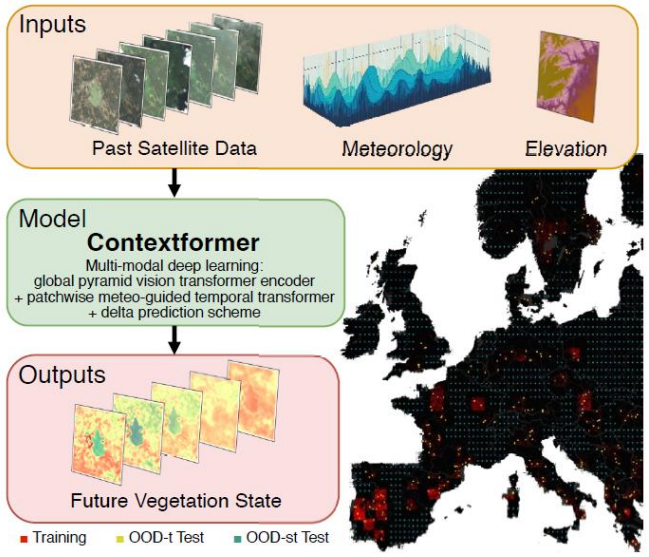


Figure 1. GreenEarthNet approach (map shows sample locations).

Limitations

- **Spatial encoding?**
- **Temporal encoding?**

Research gaps

1. Transformers may not generalize to **long, irregular** EO **time series**.
2. **Optimal context length** for forecasting is often unknown.
3. **Spatio-temporal encoding** strategies remain underexplored.

The project

GeoClimaData

1 *Article*

2 **GeoClimaData: A Global, Analysis-Ready Dataset of**
3 **Paired High-Resolution Satellite Imagery and Climate**
4 **Time Series**
5

6 **Orly Enrique Apolo-Apolo[1], Ben Somers[1], Stef Lhermitte [1]**

Images

Global Sentinel-2 record with focus on specific AOI

...

Conditions

Static environmental

...

Dynamic hydro-meteorological

ERA-5

...

...

EarthNet

Spatial extent

Temporal extent

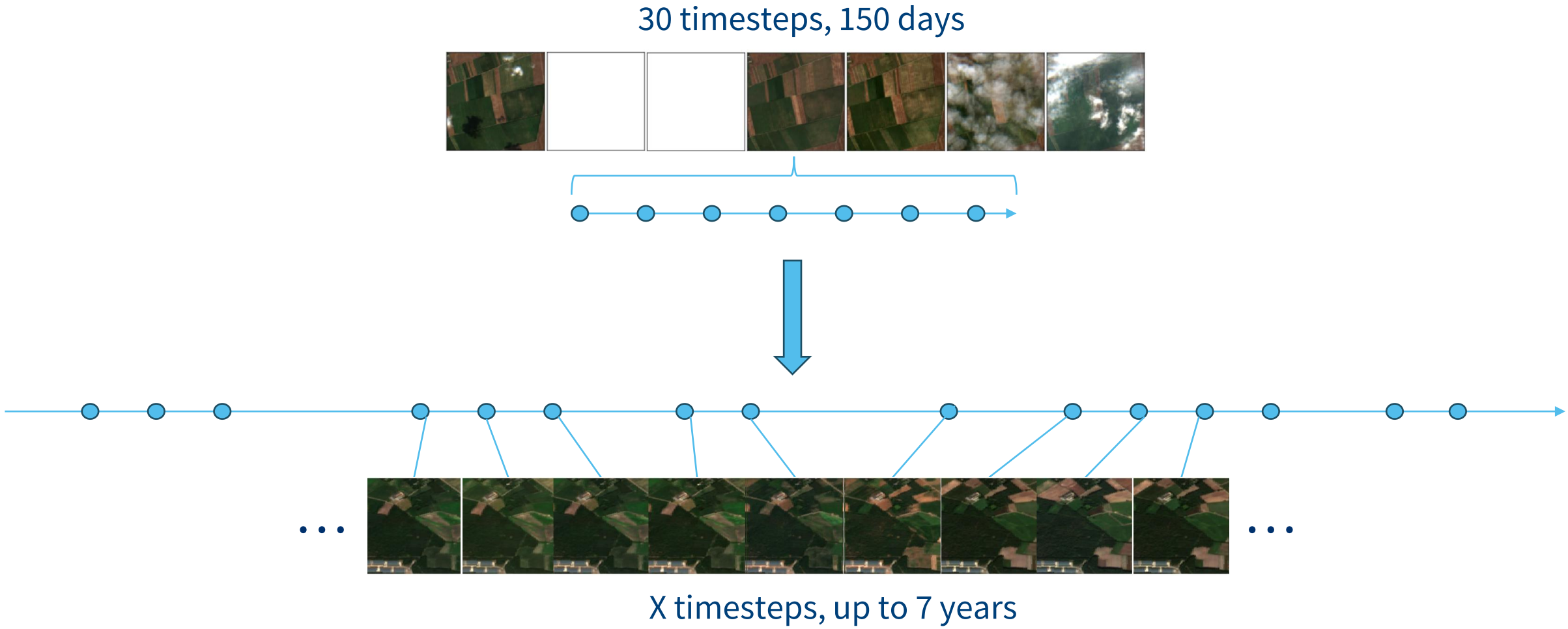
Cloud filter

		EarthNet
Spatial extent	Global	Europe
Temporal extent		
Cloud filter		

	GeoClimaData	EarthNet
Spatial extent	Global	Europe
Temporal extent	7 years (2018-2024)	5 years (2017-2022)
	Continuous	150-day datacubes
Cloud filter		

	GeoClimaData	EarthNet
Spatial extent	Global	Europe
Temporal extent	7 years (2018-2024) Continuous	5 years (2017-2022) 150-day datacubes
Cloud filter	<1 %	None

From EarthNet to GeoClimaData



Contextformer X GeoClimaData

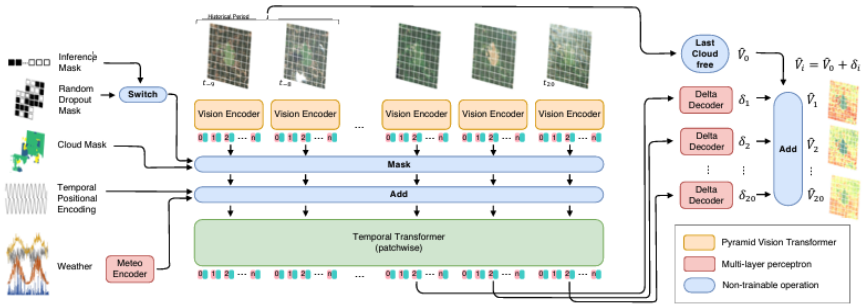
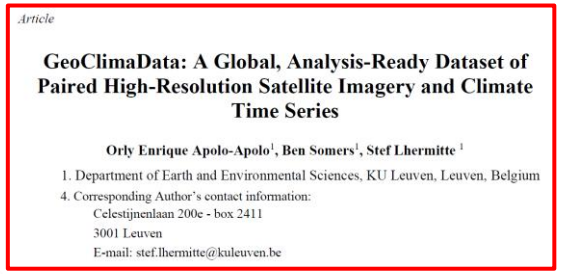


Figure 2. The architecture of our proposed Contextformer.

Contextformer

Benson et al., 2024

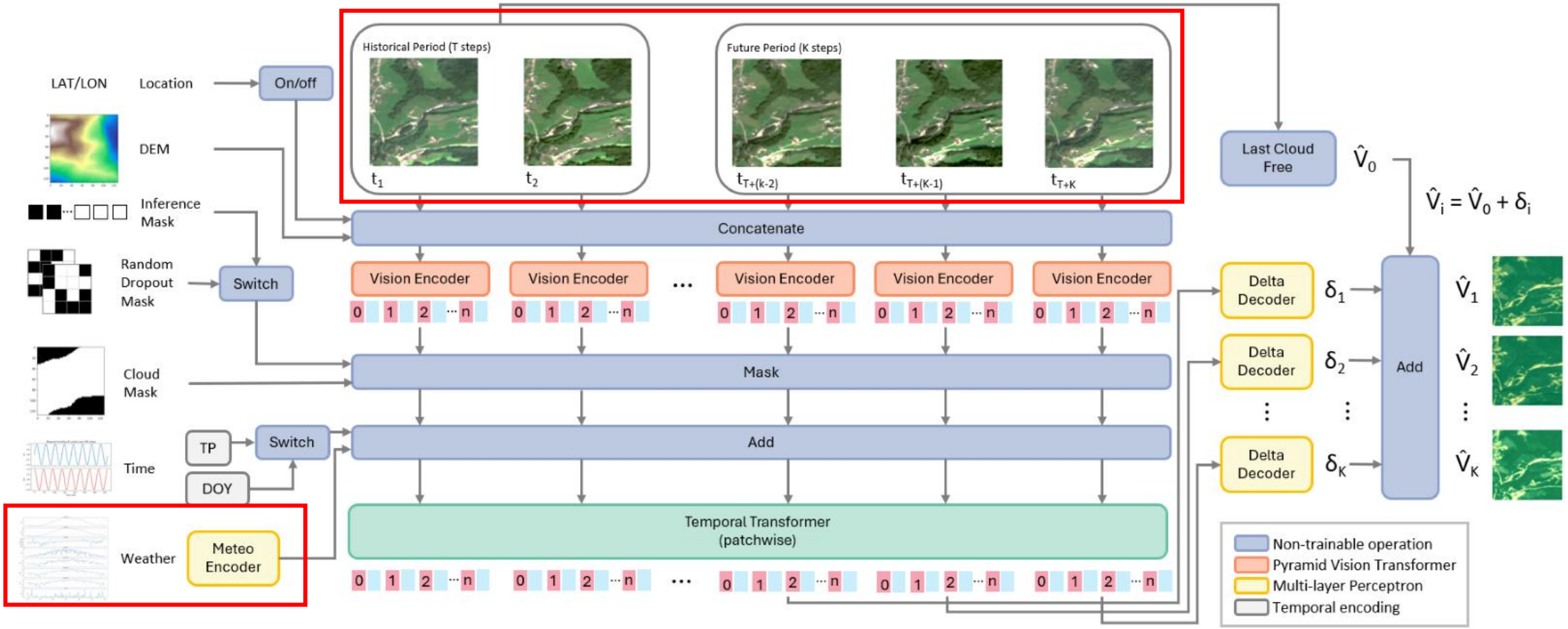
Contextformer x GeoClimaData


Article

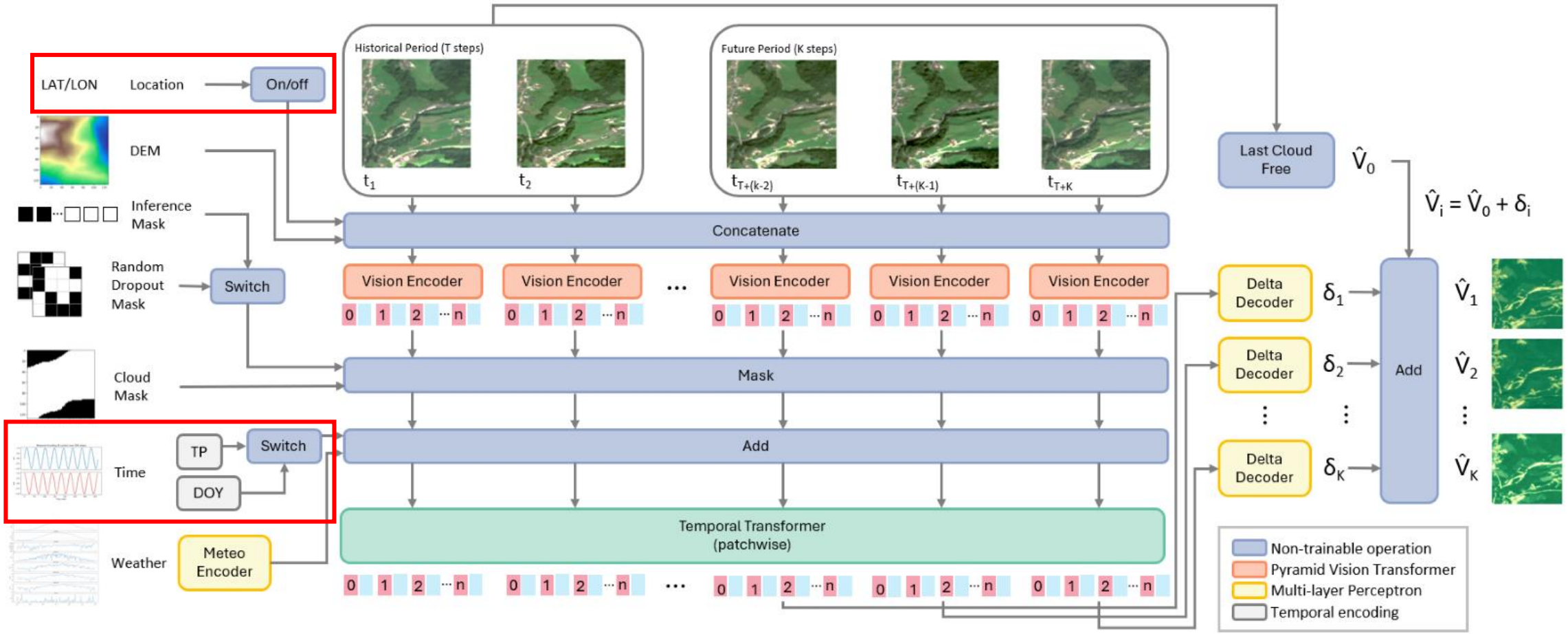
GeoClimaData: A Global, Analysis-Ready Dataset of Paired High-Resolution Satellite Imagery and Climate Time Series

Orly Enrique Apolo-Apolo[1], Ben Somers[1], Stef Lhermitte [1]

1. Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium
4. Corresponding Author's contact information:
Celestijnenlaan 200c - box 2411
3001 Leuven
E-mail: stef.lhermitte@kuleuven.be



Contextformer x GeoClimaData



Experiments

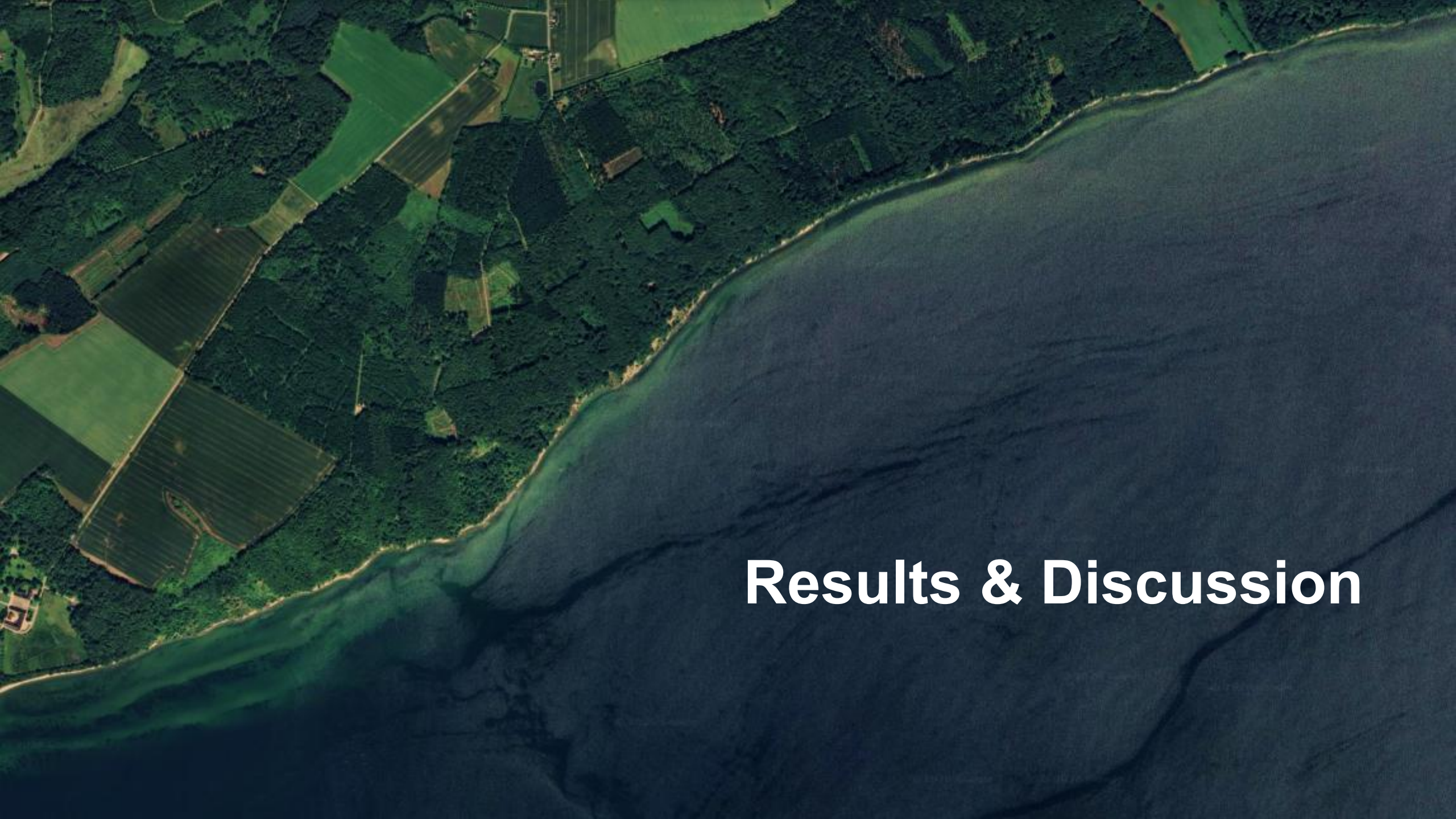
Configuration	Context length	Meteorological window	Temporal encoding	Spatial encoding
GeoClima Baseline	10 steps	5 days	TP	No
Context_20	**20 steps**	5 days	TP	No
Context_40	**40 steps**	5 days	TP	No
Meteo_31	10 steps	**31 days**	TP	No
Meteo_365	10 steps	**365 days**	TP	No
Encoding_DOY	10 steps	5 days	**DOY**	No
Encoding_TP_Spat	10 steps	5 days	TP	**Yes**

Experiments

Configuration	Context length	Meteorological window	Temporal encoding	Spatial encoding
GeoClima Baseline	10 steps	5 days	TP	No
Context_20	**20 steps**	5 days	TP	No
Context_40	**40 steps**	5 days	TP	No
Meteo_31	10 steps	**31 days**	TP	No
Meteo_365	10 steps	**365 days**	TP	No
Encoding_DOY	10 steps	5 days	**DOY**	No
Encoding_TP_Spat	10 steps	5 days	TP	**Yes**

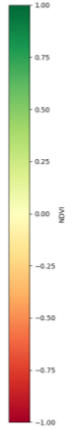
Experiments

Configuration	Context length	Meteorological window	Temporal encoding	Spatial encoding
GeoClima Baseline	10 steps	5 days	TP	No
Context_20	**20 steps**	5 days	TP	No
Context_40	**40 steps**	5 days	TP	No
Meteo_31	10 steps	**31 days**	TP	No
Meteo_365	10 steps	**365 days**	TP	No
Encoding_DOY	10 steps	5 days	**DOY**	No
Encoding_TP_Spat	10 steps	5 days	TP	**Yes**

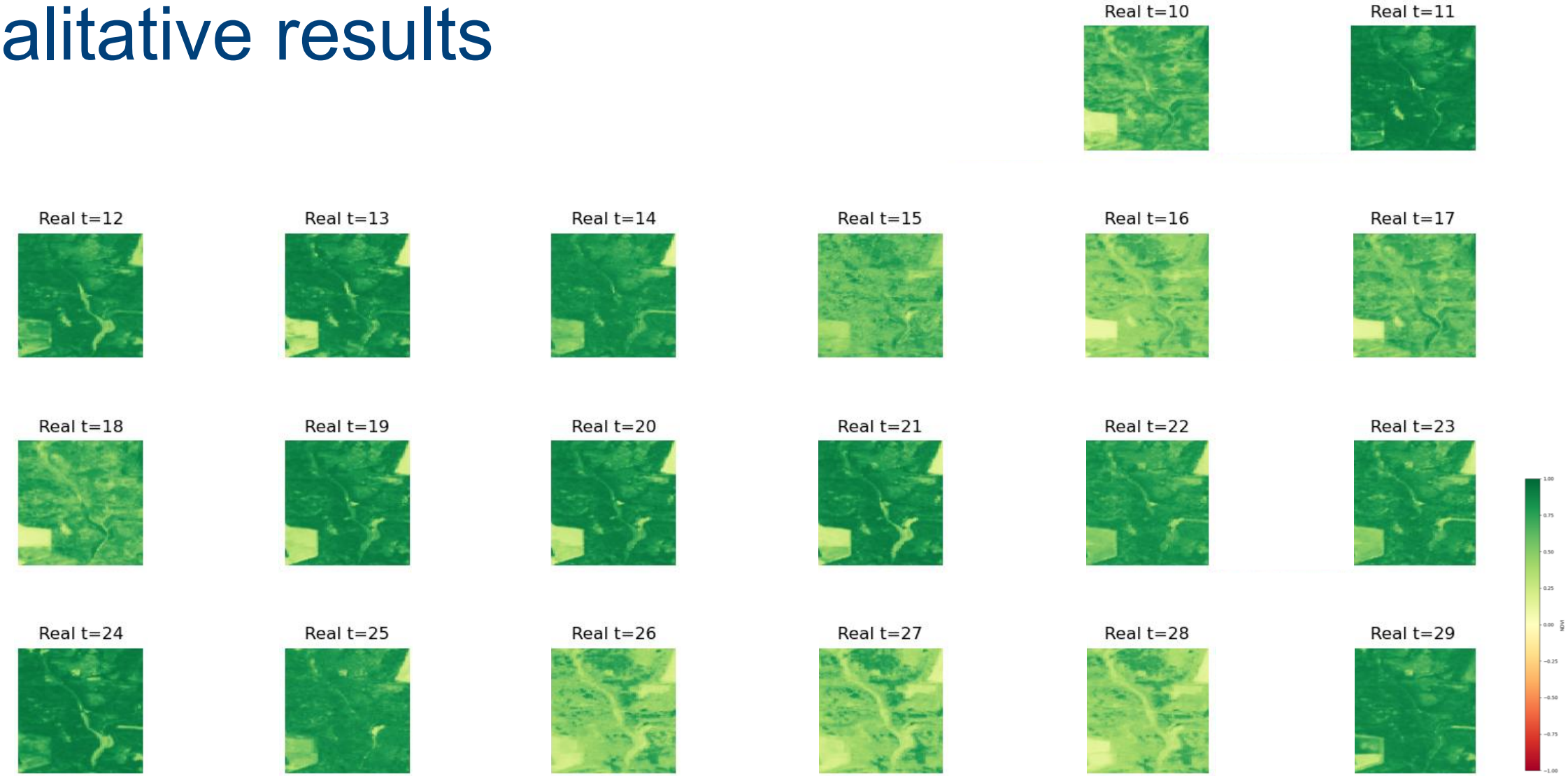


Results & Discussion

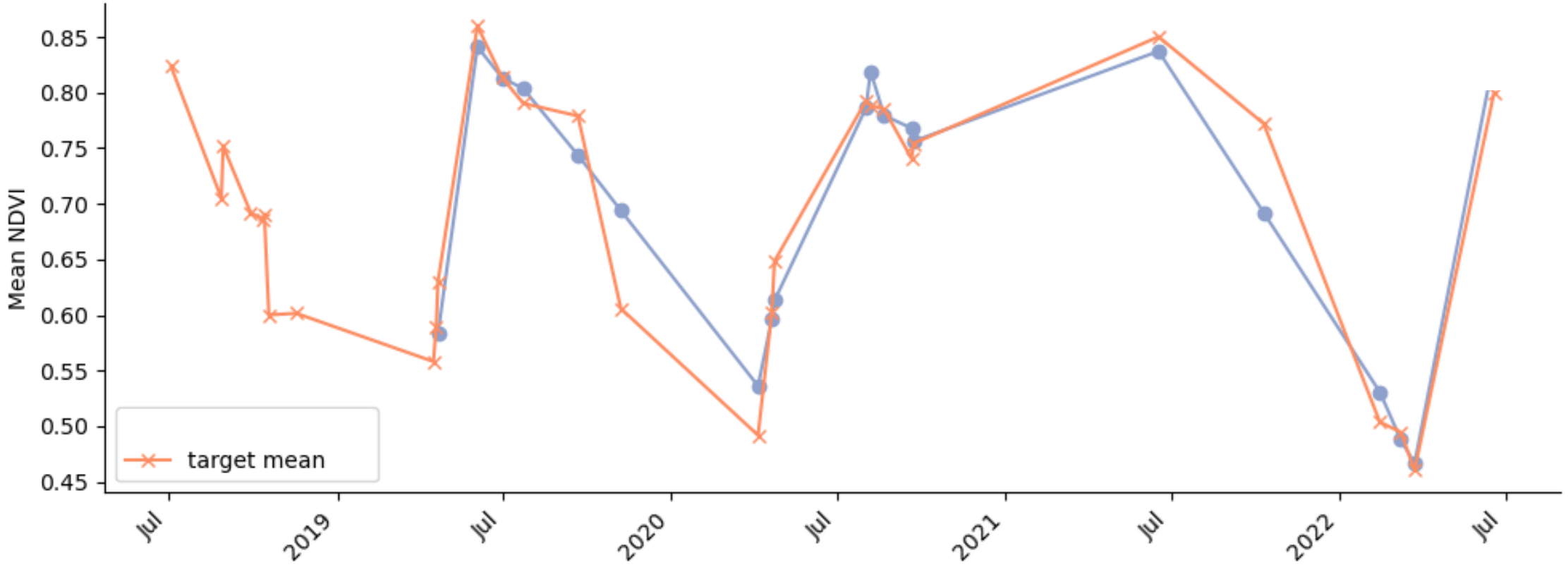
Qualitative results



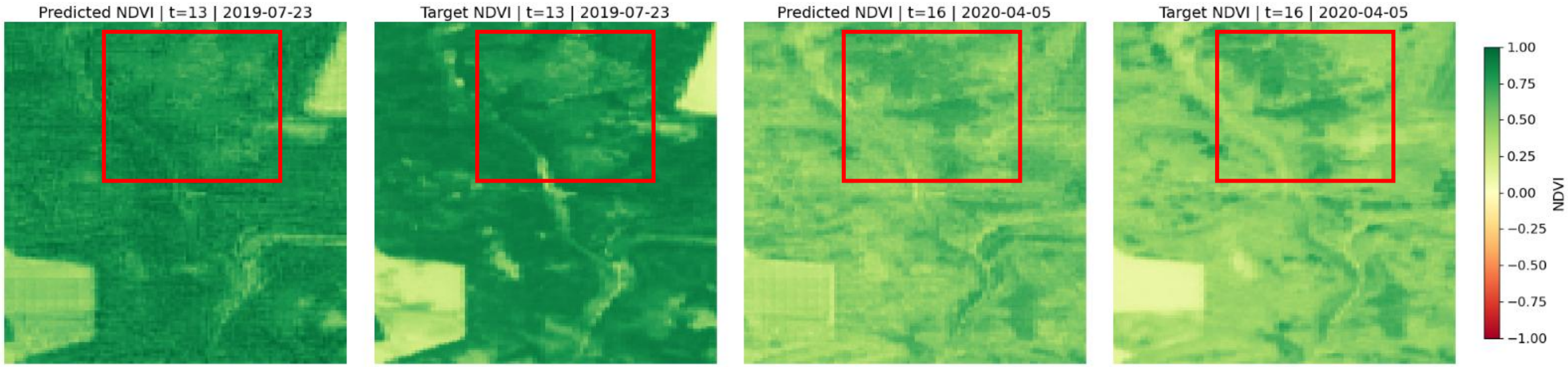
Qualitative results



Qualitative results



Qualitative results



Quantitative results

Configuration	RMSE↓	R^2↑	NSE↑	|bias|↓
Persistence	0.22 ±0.01	/	-1.70 ±0.27	0.14 ±0.01
GeoClima Baseline	0.13	0.49	-0.45	0.06
Context_20	0.13	0.50	-0.38	0.06
Context_40	0.12	0.51	-0.38	0.05
Meteo_31	0.13	0.51	-0.54	0.06
Meteo_365	0.17	0.15	-1.70	0.07
Encoding_DOY	0.18	0.47	-1.10	0.12
Encoding_TP_Spat	0.13	0.49	-0.31	0.06

Quantitative results

Configuration	RMSE↓
Persistence	0.22 ±0.01
GeoClima Baseline	0.13
Context_20	0.13
Context_40	0.12
Meteo_31	0.13
Meteo_365	0.17
Encoding_DOY	0.18
Encoding_TP_Spat	0.13

Quantitative results

Configuration	R^2↑
Persistence	/
GeoClima Baseline	0.49
Context_20	0.50
Context_40	0.51
Meteo_31	0.51
Meteo_365	0.15
Encoding_DOY	0.47
Encoding_TP_Spat	0.49

Liu et al., 2025

Quantitative results

Configuration	$R^2\uparrow$
Persistence	/
GeoClima Baseline	0.49
Context_20	0.50
Context_40	0.51
Meteo_31	0.51
Meteo_365	0.15
Encoding_DOY	0.47
Encoding_TP_Spat	0.49

Diaconu et al., 2022;
Wu et al, 2021

Quantitative results

Configuration	$R^2\uparrow$
Persistence	/
GeoClima Baseline	0.49
Context_20	0.50
Context_40	0.51
Meteo_31	0.51
Meteo_365	0.15
Encoding_DOY	0.47
Encoding_TP_Spat	0.49

Linscheid et al., 2025

Final reflection

Future research

- Expanded evaluation scope (temporal/spatial extrapolation test)
- Global geographic coverage (beyond Europe)
- Architecture exploration (model comparison)
- Meteorological time series (rather than aggregation)

Key takeaways

- Contextformer is **robust** to **long term, irregular EO** data
- Increasing **temporal context** helps, but only modestly
- **Additional complexity** does not always lead to gains
- **Careful input design** is critical for performance

Thank you

Wouter Strauven

Wouter.Strauven@kuleuven.be

www.linkedin.com/in/wouter-strauven-3130a62b5

KU Leuven, Department of Earth and Environmental Sciences, Leuven 3001, Belgium

belspo

KU LEUVEN

Key takeaways

- Contextformer is **robust** to **irregular EO** data
- Increasing **temporal context** helps, but only modestly
- **Careful input design** is critical for performance
- **Additional complexity** does not always lead to gains

Contact: Wouter.Strauven@kuleuven.be