Application-specific model selection and model weighting of Earth system models with application to regional environmental management of red tide

Ming Ye (mye@fsu.edu), Florida State University
Ahmed S. Elshall, Florida Gulf Coast University
Sven A. Kranz, Rice University
Julie Harrington, Florida State University
Xiaojuan Yang, Oak Ridge National Laboratory
Yongshan Wan, Environmental Protection Agency
Mathew Maltrud, Los Alamos National Laboratory

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Karenia brevis, single-celled, marine dinoflagellate

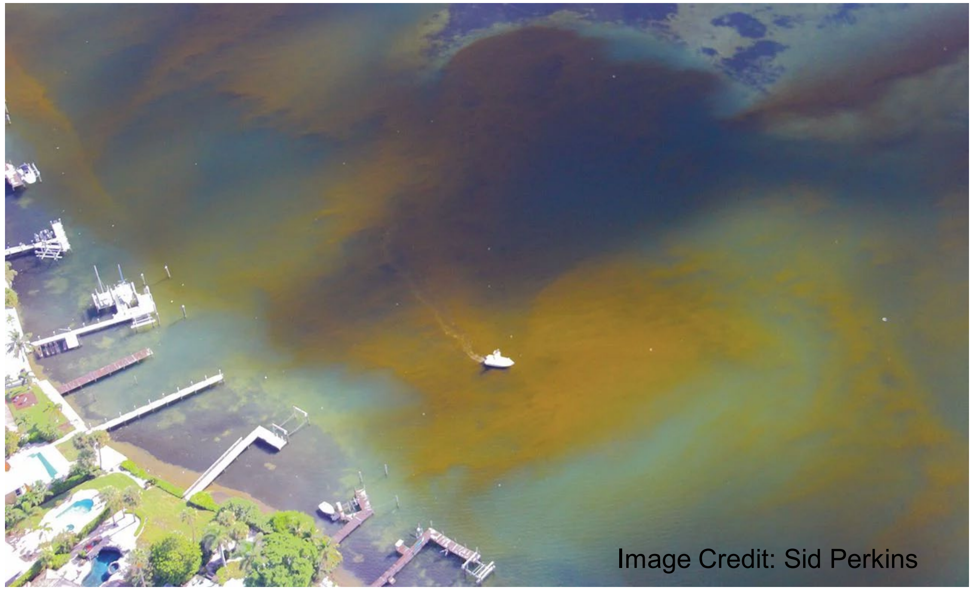
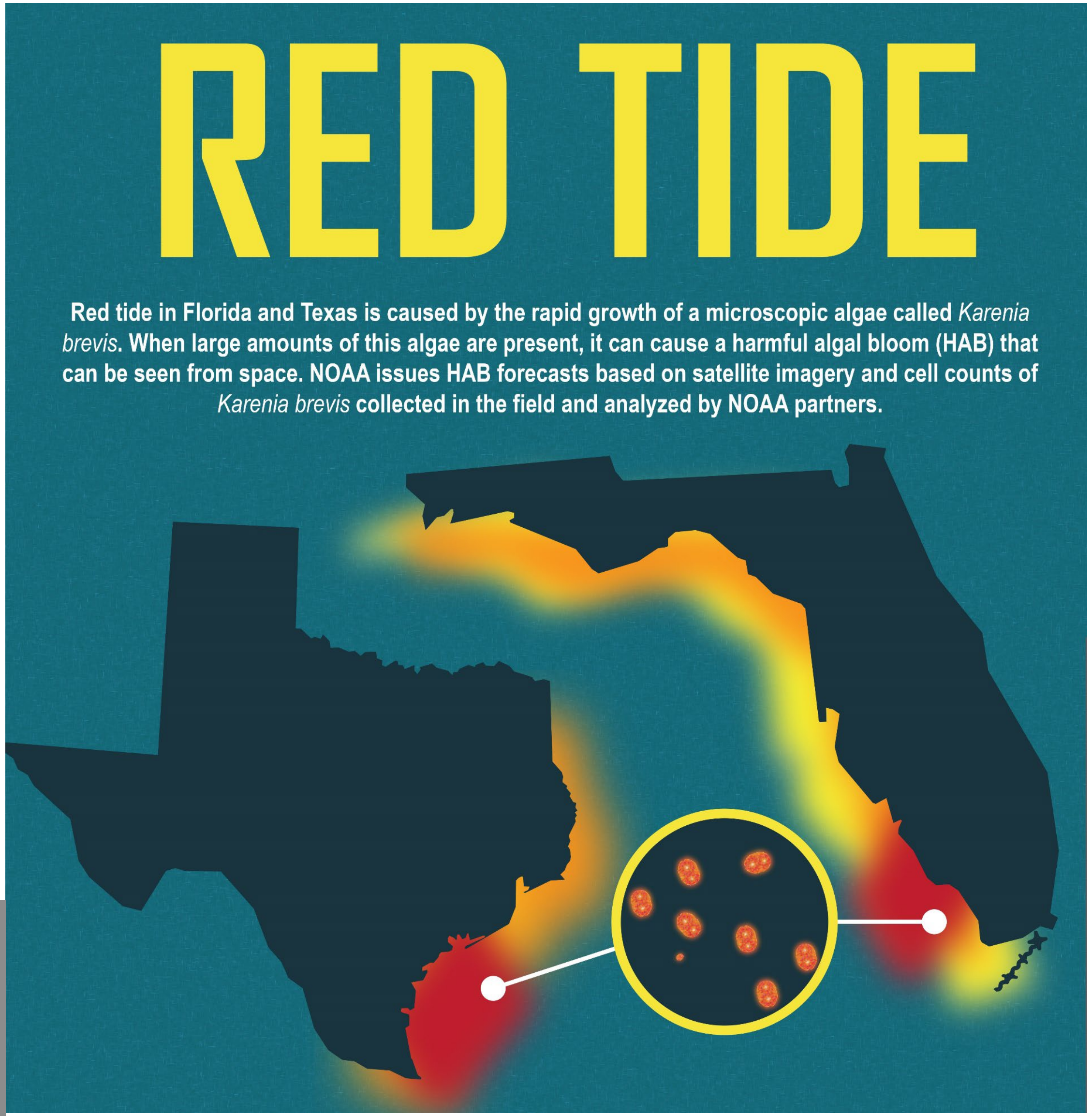


Image Credit: Sid Perkins

https://start1.org/red-tide

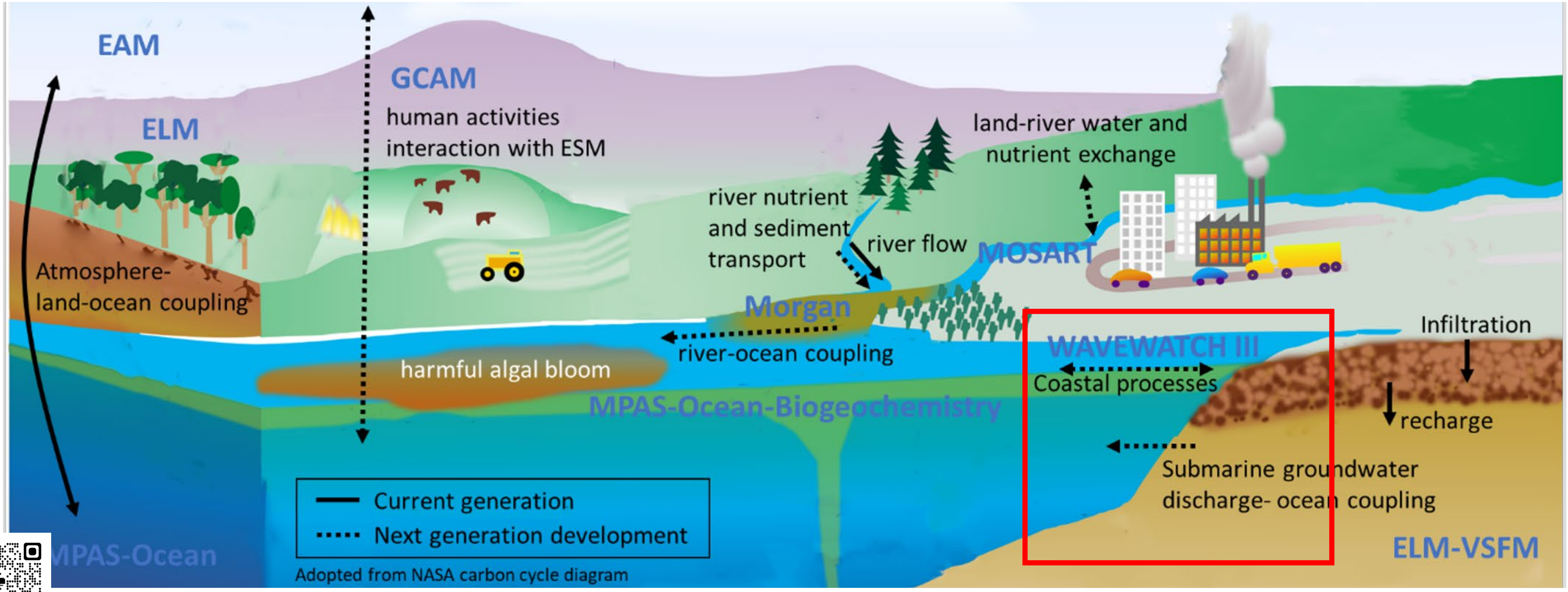
https://www.sarasotama
fitness/2022/07/red-tide-



https://oceanservice.noaa.gov/hazards/hab/gulf-mexico.html

Red tide projection is challenging as multiple drivers can alter the occurrence, intensity, and toxicity of red tides.

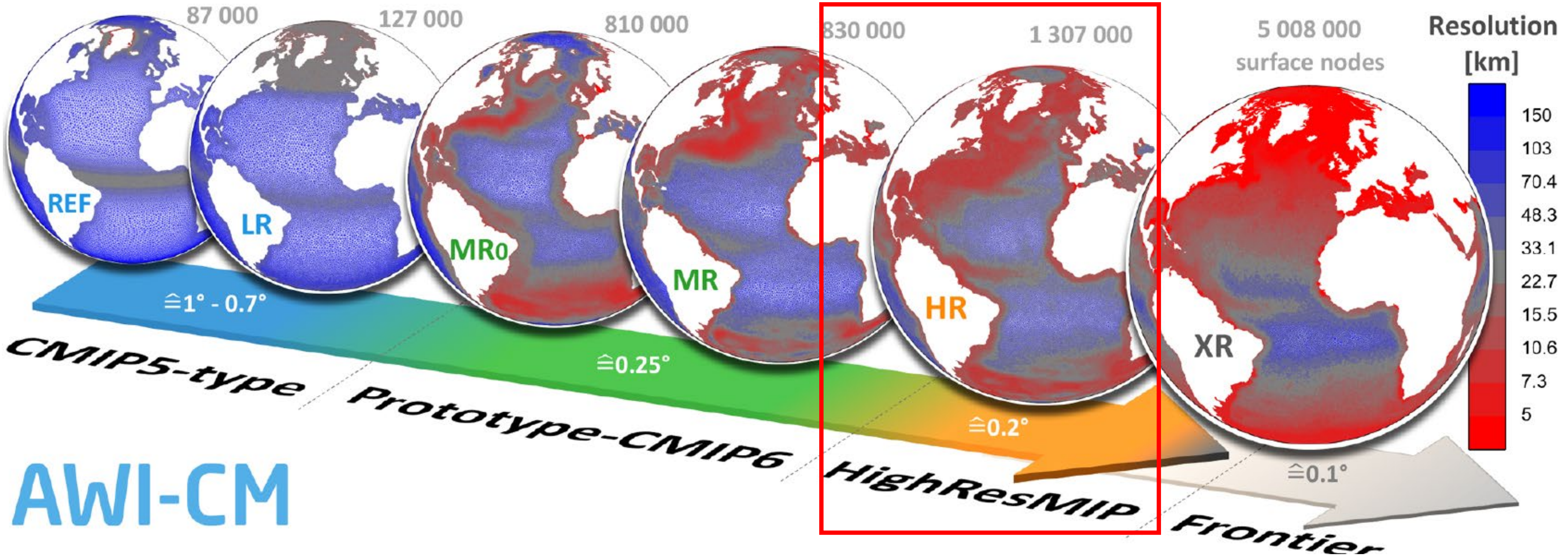
Is it possible to forecast red tides by using Earth system models outputs **directly**? **YES and NO.**



Elshall et al. 2022 EES

E3SM of the Department of Energy

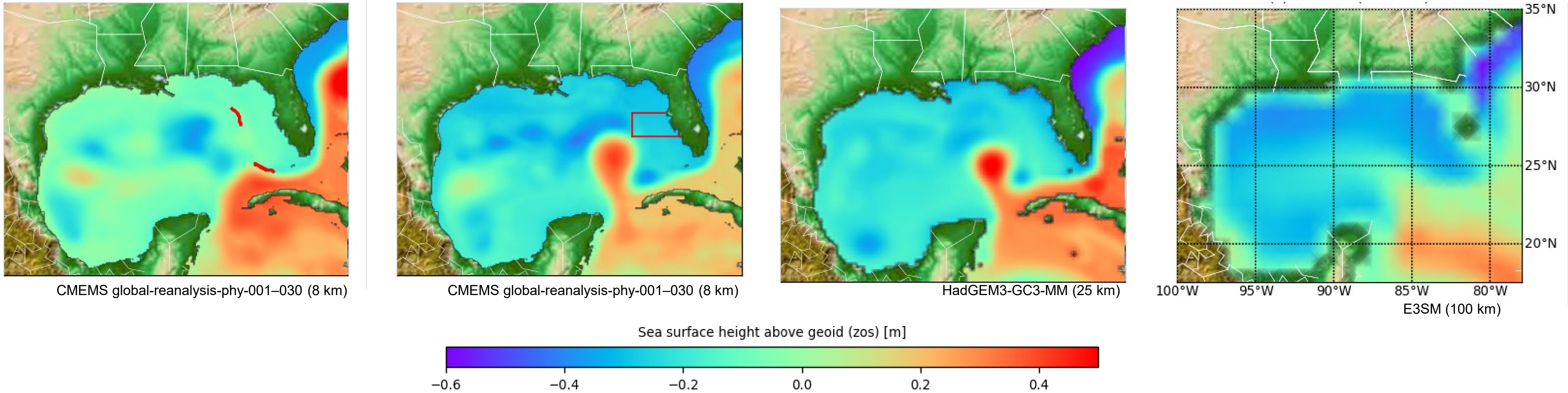
Earth system models for red tides in a changing climate based on teleconnections between global and regional phenomena



Rackow et al. (2019 GMD)

A high resolution-ESM can reproduce regional phenomena like Loop Current, a warm ocean current that drives red tides

Reanalysis Data (8km)	Reanalysis Data (8km)	**High** Resolution-ESM (25km)	**Low** Resolution-ESM (100km)
Loop Current South	Loop Current North	Loop Current North	Loop Current North
March 2010	June 2010	June 2010	June 2010

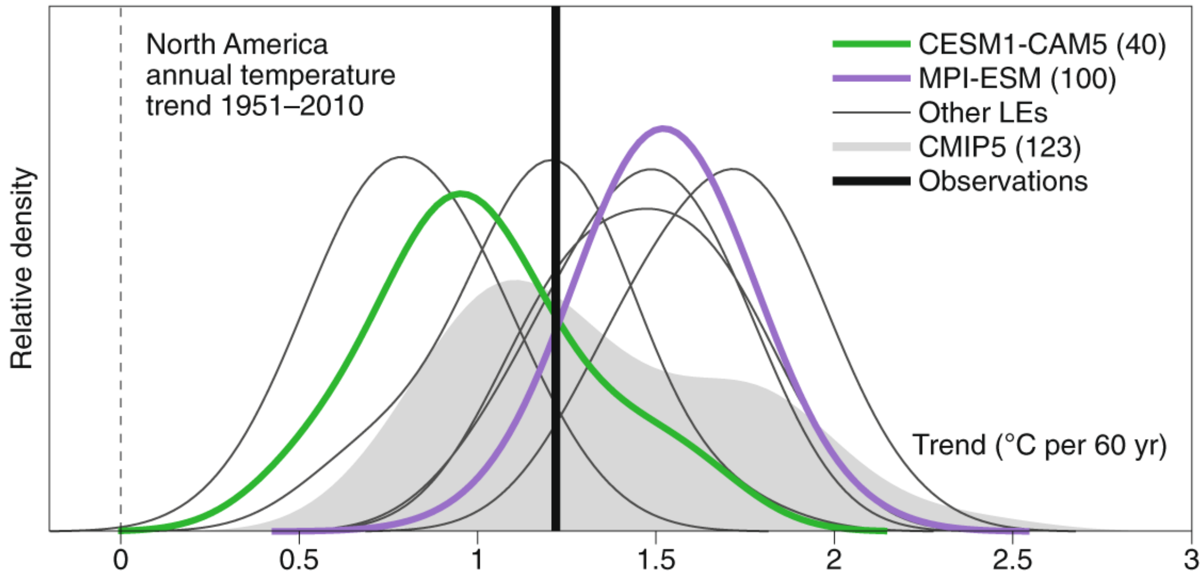


- Loop Current is an important factor that controls the occurrence of red tide.
- Maze et al. (2015) showed that the Loop current in a north position penetrating through the Gulf of Mexico is a necessarily condition for a large red tide bloom to occur (based on red tide data in the red box).
- With approximately 0.3 divisions per day, *Karenia brevis* is a slow growing dinoflagellate that requires an area with mixing slower than the growth rate to form a bloom.

Independent model subset (IMS)	Institution	Country	Model (Reference)	Experiment ID	Members	Ocean model resolution	Ocean Model	Ocean grid	ESM nominal resolution
IMS01	NCAR	USA	CESM1-CAM5-SE-HR (Chang et al. 2020)	hist-1950	r1i1p1f1	0.1° (11 km) nominal resolution	POP2	POP2-HR	25 km
IMS02	CMCC	Italy	CMCC-CM2-HR4 (Cherchi et al. 2019)	hist-1950	r1i1p1f1	0.25° from the Equator degrading at the poles	NEMO v3.6	ORCA025	25 km
			CMCC-CM2-VHR4 (Cherchi et al. 2019)	hist-1950	r1i1p1f1	0.25° from the Equator degrading at the poles	NEMO v3.6	ORCA025	25 km
IMS03	CNRM-CERFACS	France	CNRM-CM6-1-HR (Voldoire et al. 2019)	hist-1950	r(1-3)i1p1f2	0.25° (27-28 km) nominal resolution	NEMO v3.6	eORCA025	25 km
			CNRM-CM6-1-HR (Voldoire et al. 2019)	historical	r1i1p1f2	0.25° (27-28 km) nominal resolution	NEMO v3.6	eORCA025	25 km
IMS04	DOE-E3SM-Project	USA	E3SM-1-0 (Golaz et al. 2109)	historical	r(1-5)i1p1f1	60 km in mid-latitudes and 30 km at the equator and poles	MPAS-O	EC60to30	100 km
IMS05	EC-Earth-Consortium	Europe	EC-Earth3P (Haarsma et al. 2020)	hist-1950	r(1-3)i1p2f1	about 1° (110 km)	NEMO v3.6	ORCA1	100 km
IMS06	EC-Earth-Consortium	Europe	EC-Earth3P-HR (Haarsma et al. 2020)	hist-1950	r(1-3)i1p2f1	about 0.25° (27-28 km)	NEMO v3.6	ORCA025	25 km
IMS07	ECMWF	Europe	ECMWF-IFS-HR (Roberts et al. 2018)	hist-1950	r(1-6)i1p1f1	25 km nominal resolution	NEMO v3.4	ORCA025	25 km
IMS08			ECMWF-IFS-MR (Roberts et al. 2018)	hist-1950	r(1-3)i1p1f1	25 km nominal resolution	NEMO v3.4	ORCA025	25 km
IMS09	NOAA-GFDL	USA	GFDL-CM4 (Held et al 2019)	historical	r1i1p1f1	0.25° (27-28 km) nominal resolution	MOM6	tri-polar grid	50 km
			GFDL-ESM4 (Held et al 2019)	historical	r(2-3)i1p1f1	0.25° (27-28 km) nominal resolution	MOM6	tri-polar grid	50 km
IMS10	NERC	UK	HadGEM3-GC31-HH (Roberts et al. 2019)	hist-1950	r1i1p1f1	8 km nominal resolution	NEMO v3.6	ORCA12	10 km
	MOHC-NERC	UK	HadGEM3-GC31-HM (Roberts et al. 2019)	hist-1950	r1i(1-3)p1f1	25 km nominal resolution	NEMO v3.6	ORCA12	50 km
IMS11	MOHC	UK	HadGEM3-GC31-MM (Roberts et al. 2019)	hist-1950	r1i(1-3)p1f1	25 km nominal resolution	NEMO v3.6	ORCA025	100 km
			HadGEM3-GC31-MM (Roberts et al. 2019)	historical	r(1-4)i1p1f3	25 km nominal resolution	NEMO v3.6	ORCA025	25 km

Ensemble Modeling Approaches

An Illustration



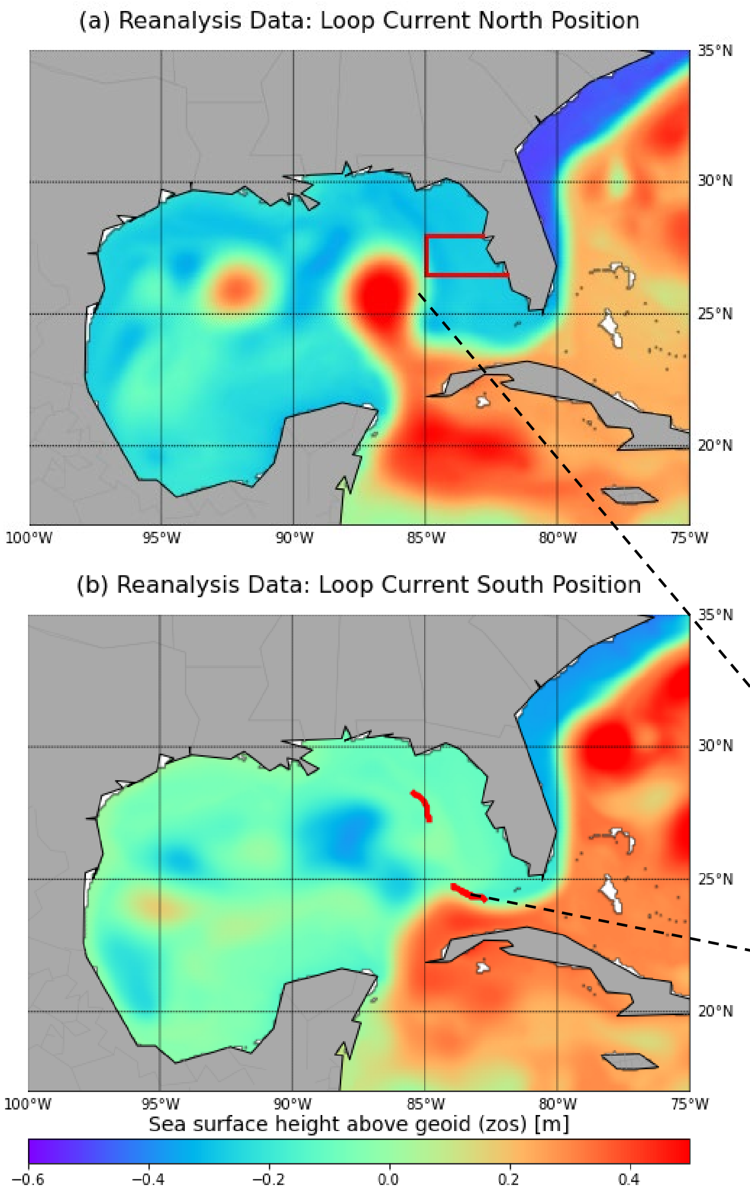
https://www.nature.com/articles/s41558-020-0731-2

Ensemble ESMs for loop current

- 41 CMIP6 model runs from 14 different models developed by eight institutes
- Prescreening-based subset selection

  Excluding non-representing models
- Application-specific optimal model weighting

Prescreening-based Subset Selection: Loop Current



CMIP6: zos - Sea Surface Height Above Geoid

Zos anomaly of model ***M_k*** (the k-th model in the ensemble)

$$h_t = \max_{h_n}\left(\Delta_m\left[E_l\left[E_k\left(E_j(h_{j,k,l,m,n,t} \mid \boxed{M_k})\right)\right]\right]\right)$$

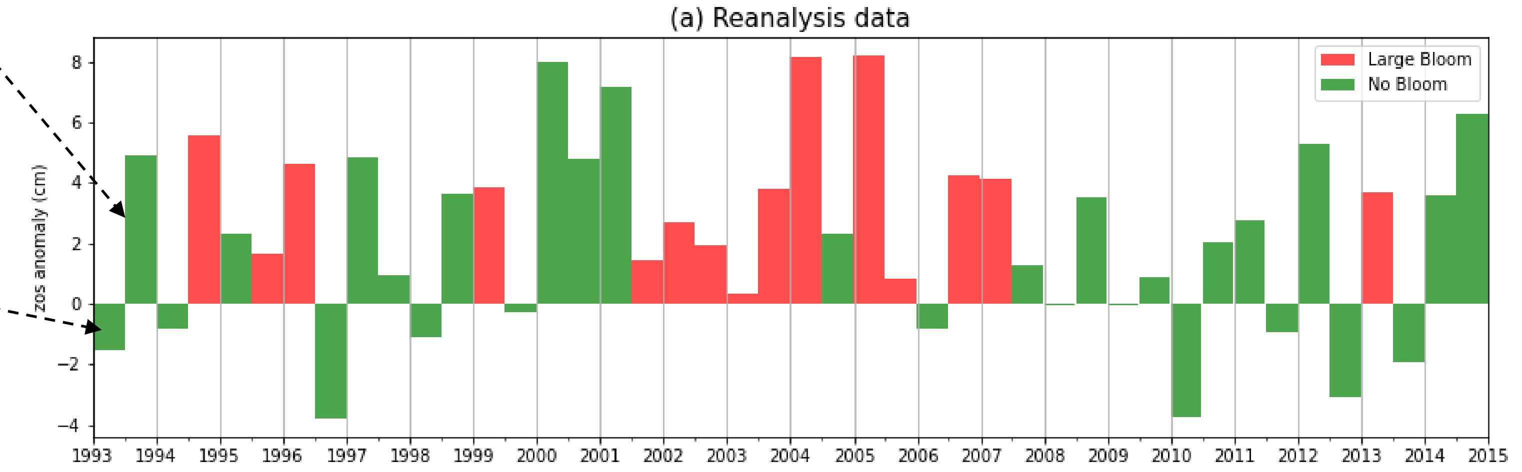
Is the maximum difference of the zos data at the north and the south segment.

LC-N: Loop Current in the north position

$$H_{LC-N}(h_t) = \begin{cases} 1, & h_t \geq 0 \\ 0, & h_t < 0 \end{cases}$$

LC-S: Loop Current in the south position

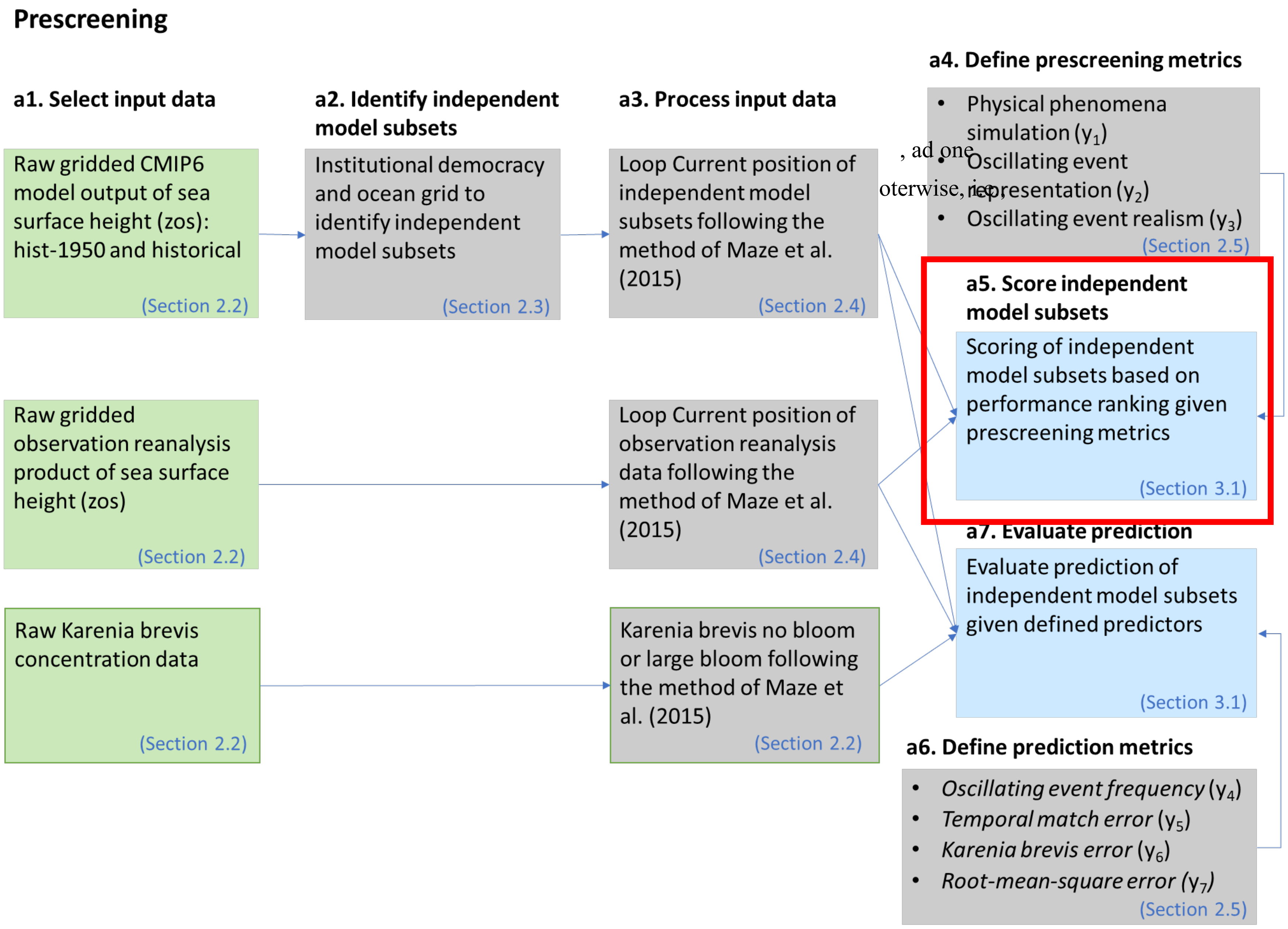
$$H_{LC-S}(h_t) = \begin{cases} 1, & h_t < 0 \\ 0, & h_t \geq 0 \end{cases}$$



H_{LC-N}

H_{LC-S}

LC-N is a necessary condition of red tide large bloom.



Prescreening

Three prescreening metrics based on a model's ability to reproduce main features of the physically interpretable relationships of interest (prior info).

Oscillating event representation

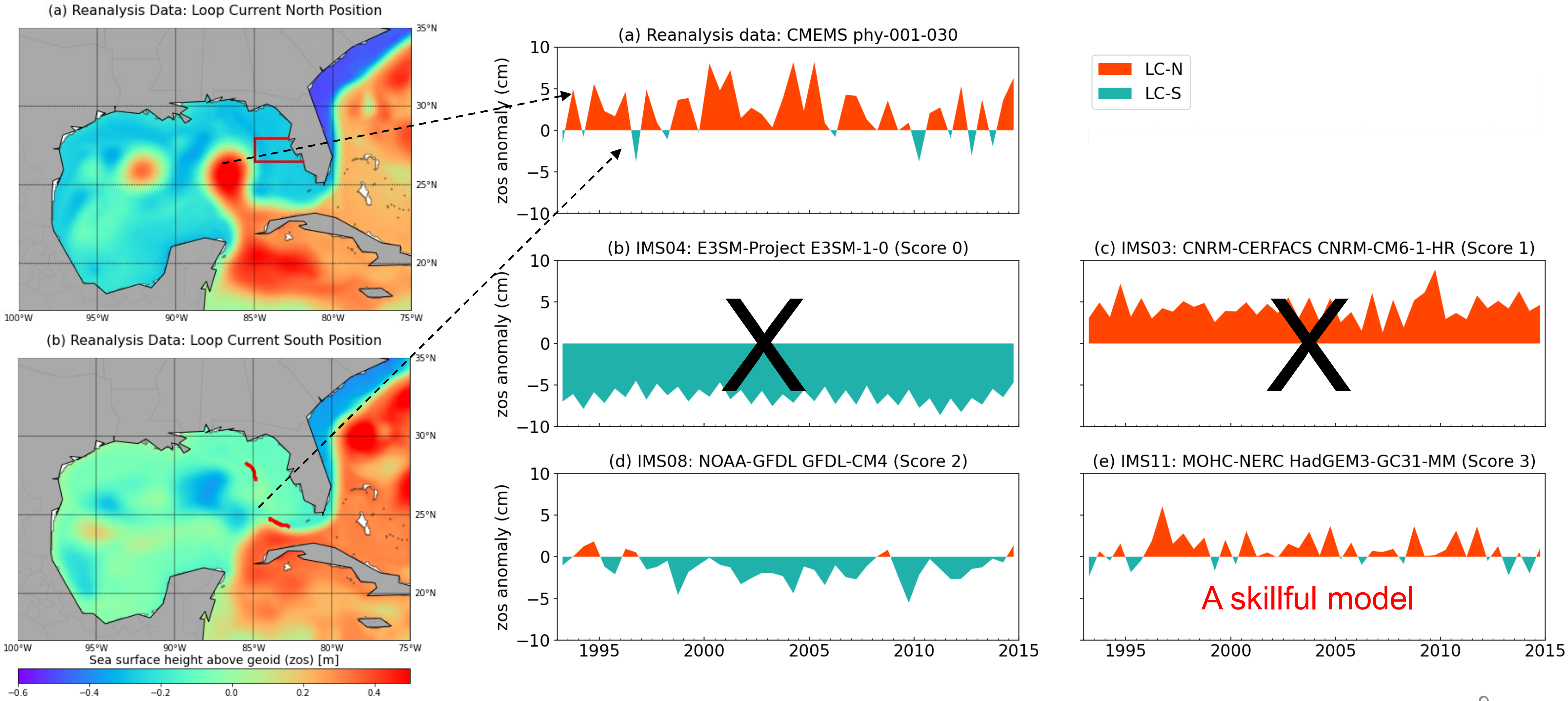
If the sea surface height is consistently higher at the north segment than at the south segment, then the model is unable to represent alternation of LC-N and LC-S.

Scoring

Score = 1 or 0

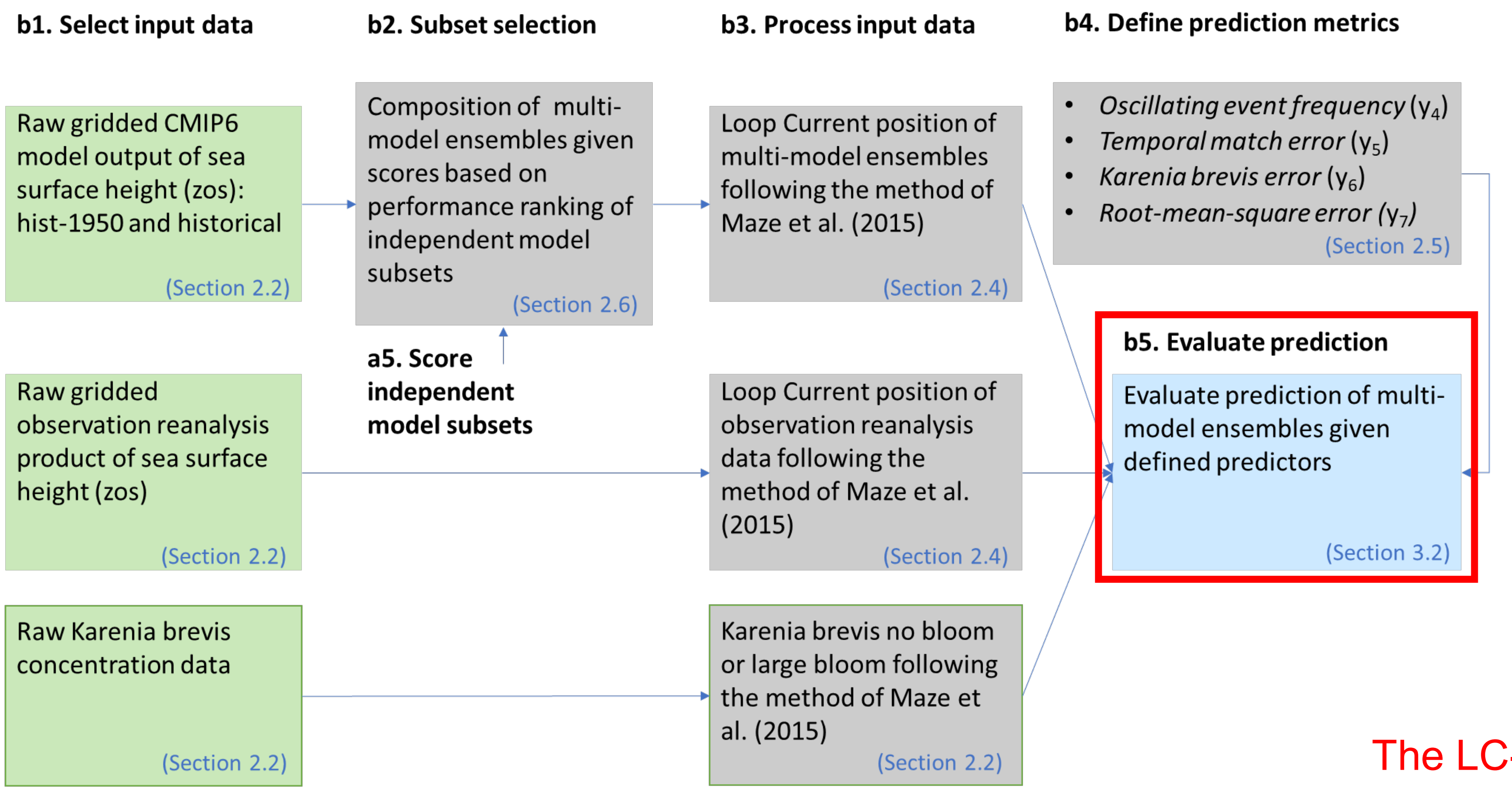
$$y_2 = \begin{cases} 1, & 0 < \sum_{t=1}^{T} H_{LC-N}(h_t) < T \\ 0, & \sum_{t=1}^{T} H_{LC-N}(h_t) = T \end{cases}$$

Prescreening-based subset selection can find representative and skillful models for a given application



Subset Selection

Subset selection



Four metrics to evaluate predictive performance.

Oscillating event frequency
the ratio of the number of a LC south position (LC-S) to the total number of intervals

$$y_4 = \frac{\sum_{t=1}^{T} H_{LC-S}(h_t)}{T}$$

The LC-S ratio is 0.27 for reanalysis data.

Using the prescreening-based subset selection improves the simulation of Loop Current.

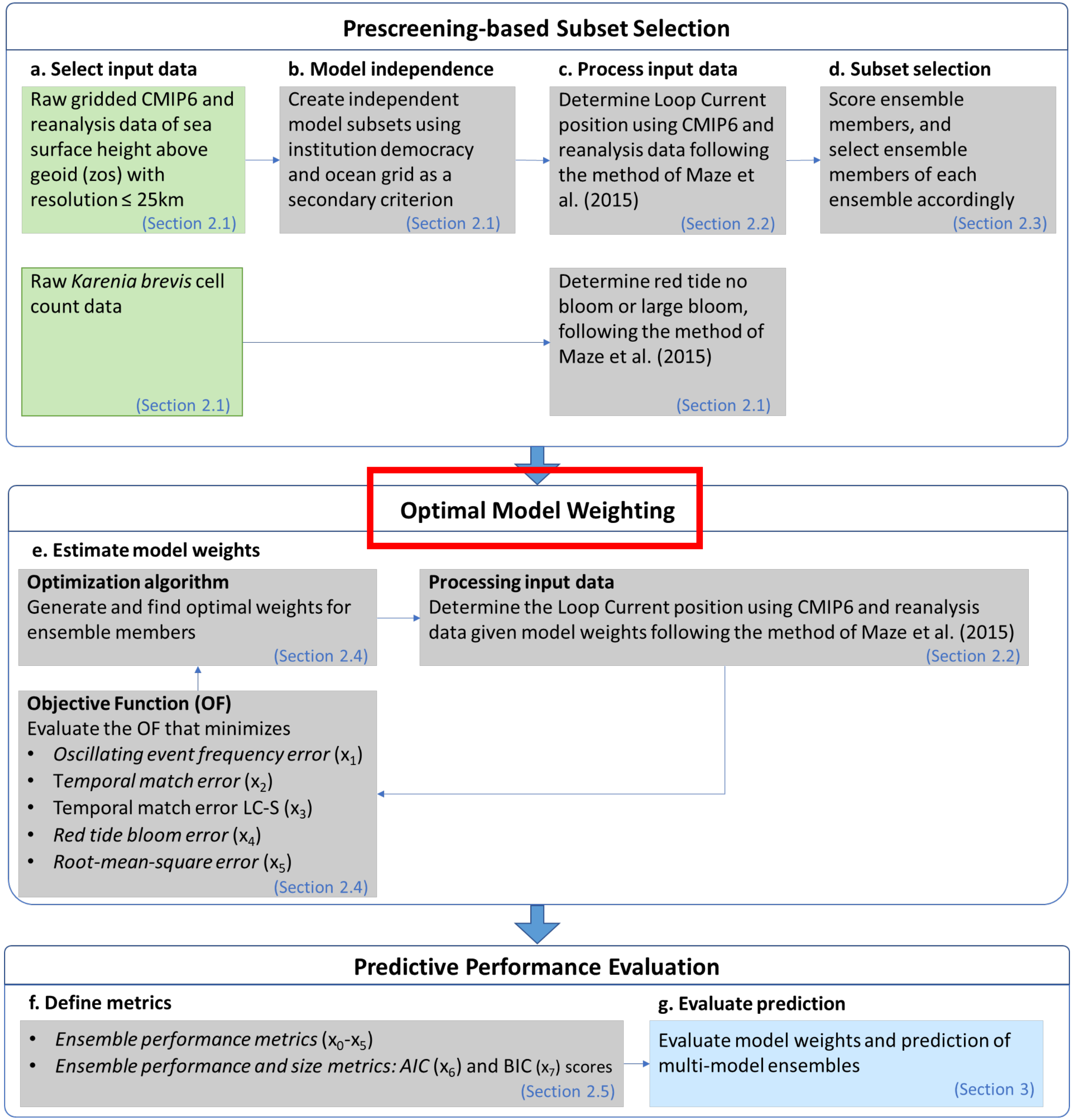
Ensemble including all models (SME3210)

Excluding models based on prior information (SME321X)

Non-representative models are additionally excluded based on prescreening (SME32XX)

Only representative and skillful models are included based on prescreening (SME3XXX)

- The ensemble prescreening is empirical, but practical and flexible for using prior knowledge on key features of interest.
- The presented subset-selection method is flexible as it scores each model given multiple binary criteria.
- We provides a straightforward and easy-to-implement approach that can be used for many climate services in different sectors as needed.



Application-specific optimal model weighting

Model weight w

$$\sum_{k=1}^{K} w_k = 1$$

$$\min_{w_k} f = \min_{w_k} \left[\prod_{i=1}^{5} (x_i + 1)^{c_i} \right]$$

Oscillating event count error

$$x_1 = \left| \sum_{n=1}^{N} H_{LC-S}(h_n) - \sum_{n=1}^{N} H_{LC-S}(h_{n,obs}) \right|$$

Minimize the objective function using the covariance matrix adaptation evolution strategy (CMA-ES)

While we can use model weighting instead of subset selection, a critical pitfall of model weighting is error cancelation

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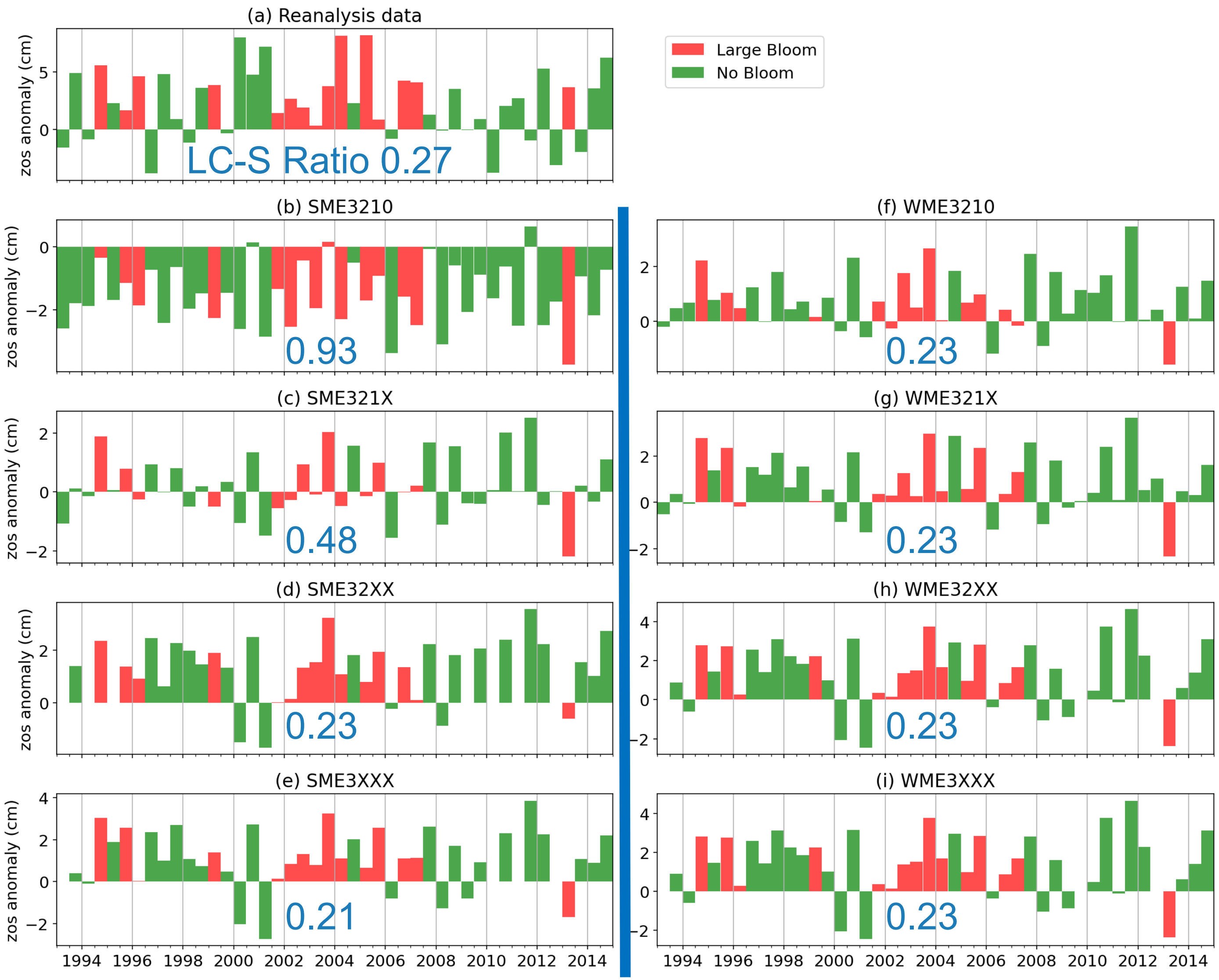
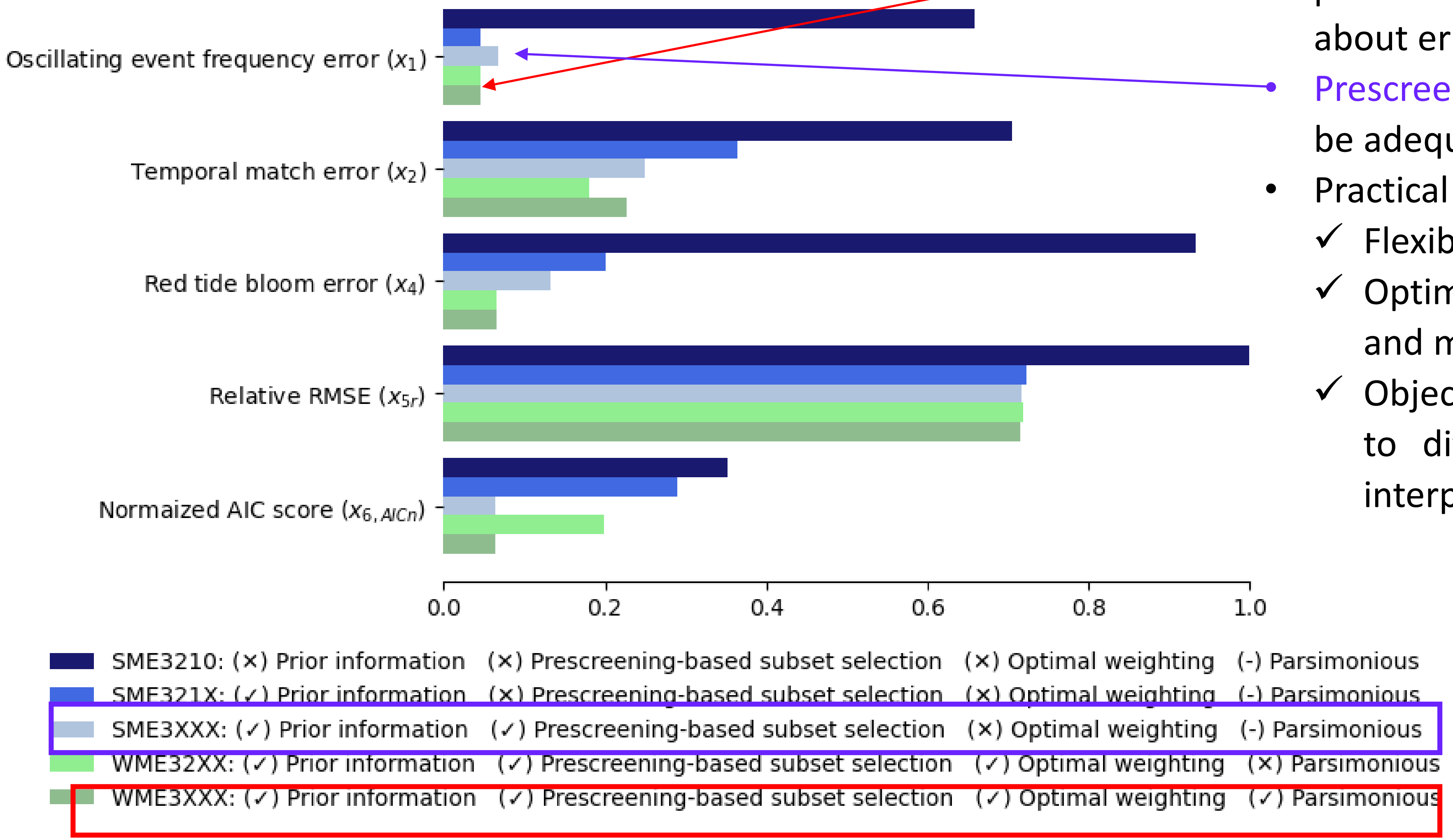


Model weighting

Application-specific optimal model weighting



- Optimal model weighting can improve predictive performance, but be cautious about error cancellation.
- Prescreening-based subset selection may be adequate.
- Practical advantage:
  - ✓ Flexibility in ensemble calibration
  - ✓ Optimization with multiple objectives and multiple metrics
  - ✓ Objectives and metrics can be adaptive to different problems and physically interpretable.

Selected results (off-line or maybe online in the future) of Earth System Models can be used directly for regional problems, not red tide yet.

Prescreening-based subset selection is useful for developing an application-specific ensemble given a regional phenomenon.

Questions?

FLORIDA GULF COAST UNIVERSITY

FLORIDA STATE UNIVERSITY 1851

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

OAK RIDGE National Laboratory

Los Alamos NATIONAL LABORATORY EST. 1943

NSF

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