Climate and Connectivity in the Coral Triangle

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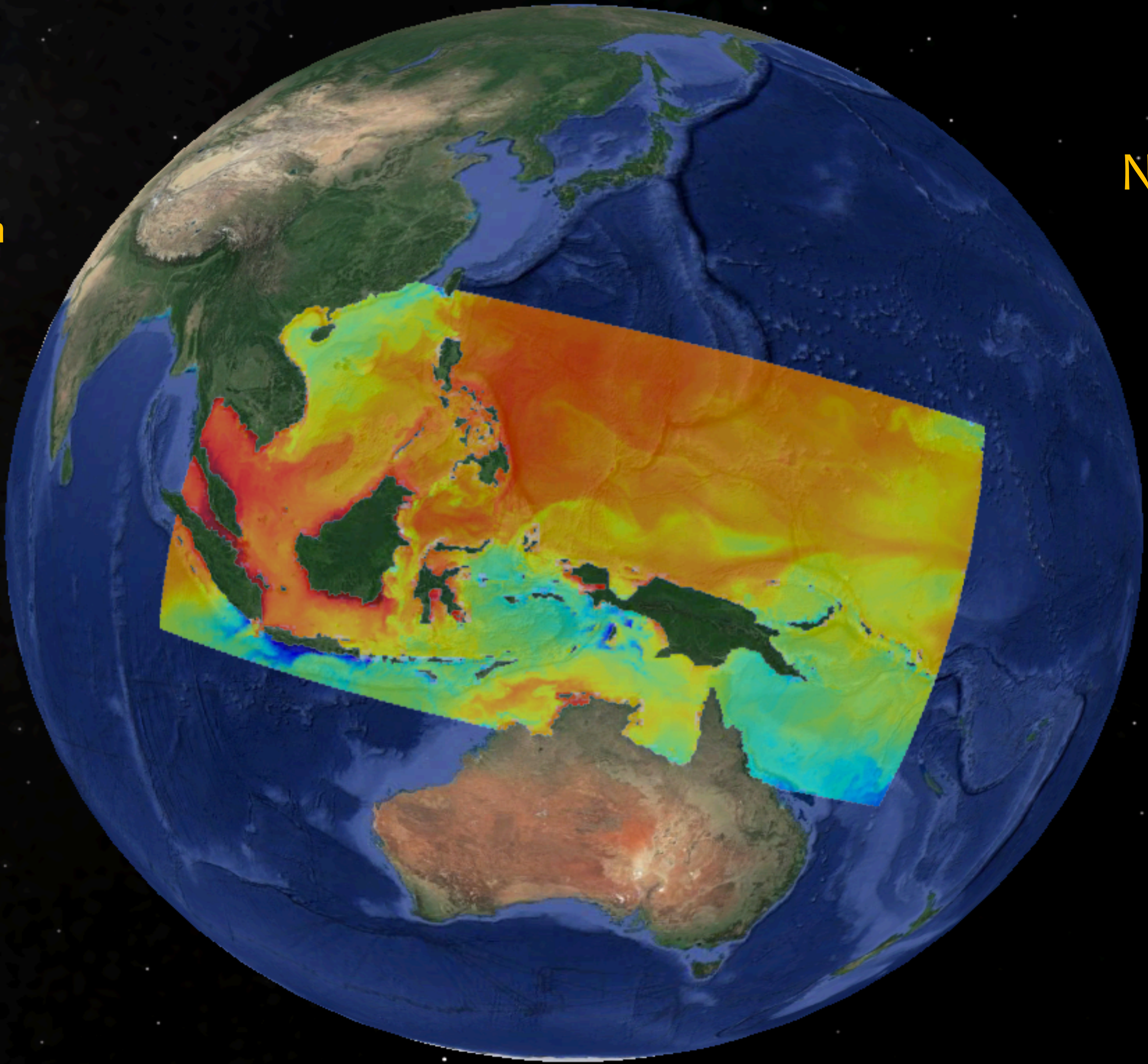

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Reef conservation in the Coral Triangle?

Motivation:

Coral reefs are degrading quickly and a major reason for the degradation is a warming and more acidic ocean.

However, they have tremendous value to humans and should be conserved

Problem:

Conservation efforts require an understanding of:

1. The exposure and sensitivity of coral reefs to climate change
2. The ability to recover, e.g. recolonizing via larval-dispersal following a bleaching event

Our approach:

Use models to inform conservation strategies that allow reefs to survive into the future

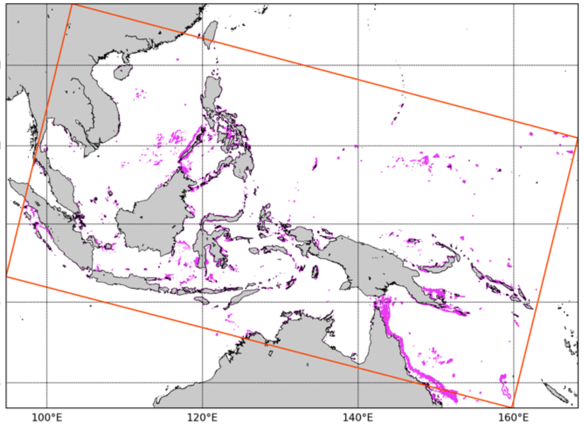
Our Coral Triangle World

Heat Budget
- Mechanisms
- Regional differences

Coral Bleaching
- Past analysis
- Future projections

Oceanography
- Circulation changes
- Effect of scale

Turbulent mixing
- Barriers to larval dispersal



Connectivity
- Spratly Islands connectivity
- CT connectivity and climate
- Sensitivity of larval biology
- Life history strategies
- Genetics?

Biogeochemistry
- Productivity
- Ocean acidification

Metapopulation Modeling
- Competition
- Disturbance (e.g. bleaching)

NCAR: Joanie Kleypas, Fred Castruccio, Diane Thompson

Rutgers Institute of Marine and Coastal Sciences: Enrique Curchitser, Malin Pinsky, Liz Drinkard, Sarah Lietzke

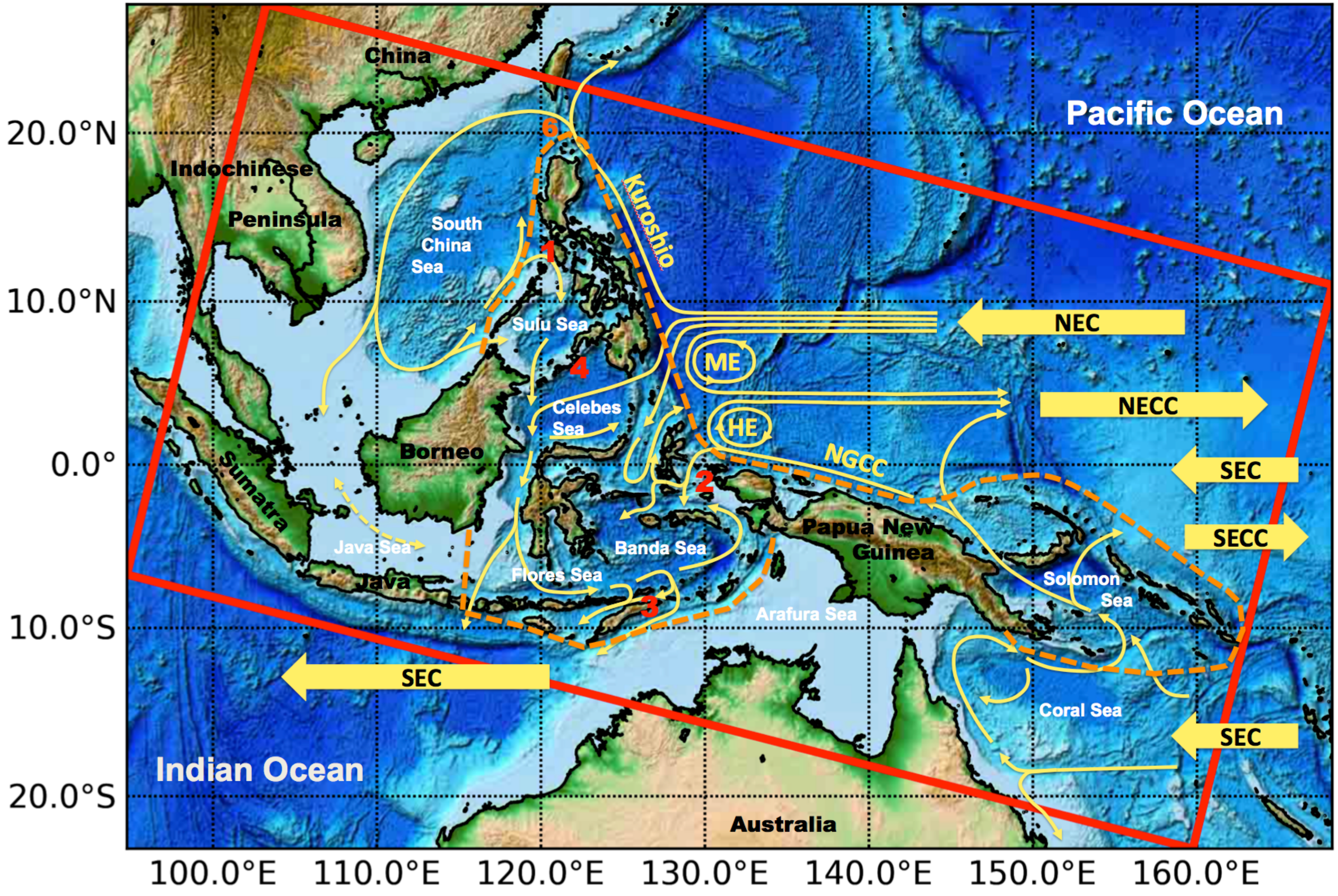
Stockholm University: James Watson

The Nature Conservancy (Protecting nature. Preserving life.): Elizabeth Mcleod, Rod Salm

Princeton University: Lisa McManus, Simon Levin

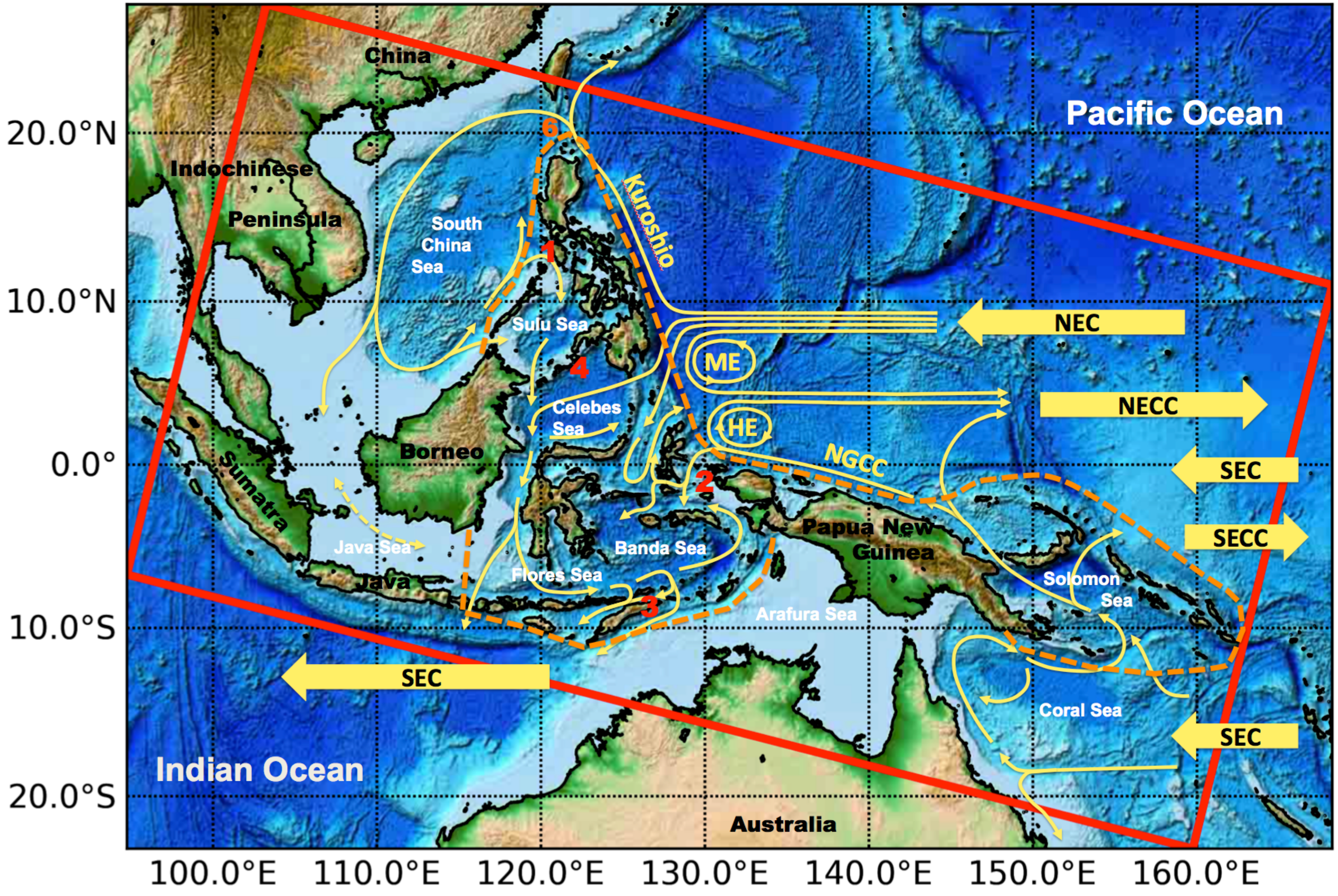
NOAA: Rusty Brainard, Roberto Venegas, And others!

One challenge: Complex oceanography



Castruccio et al., 2013, *J. Geophys. Res.*

Many opportunities: Complex oceanography



Castruccio et al., 2013, *J. Geophys. Res.*

Regional Ocean Model System

The Coral Triangle Implementation

CT-ROMS Specifications

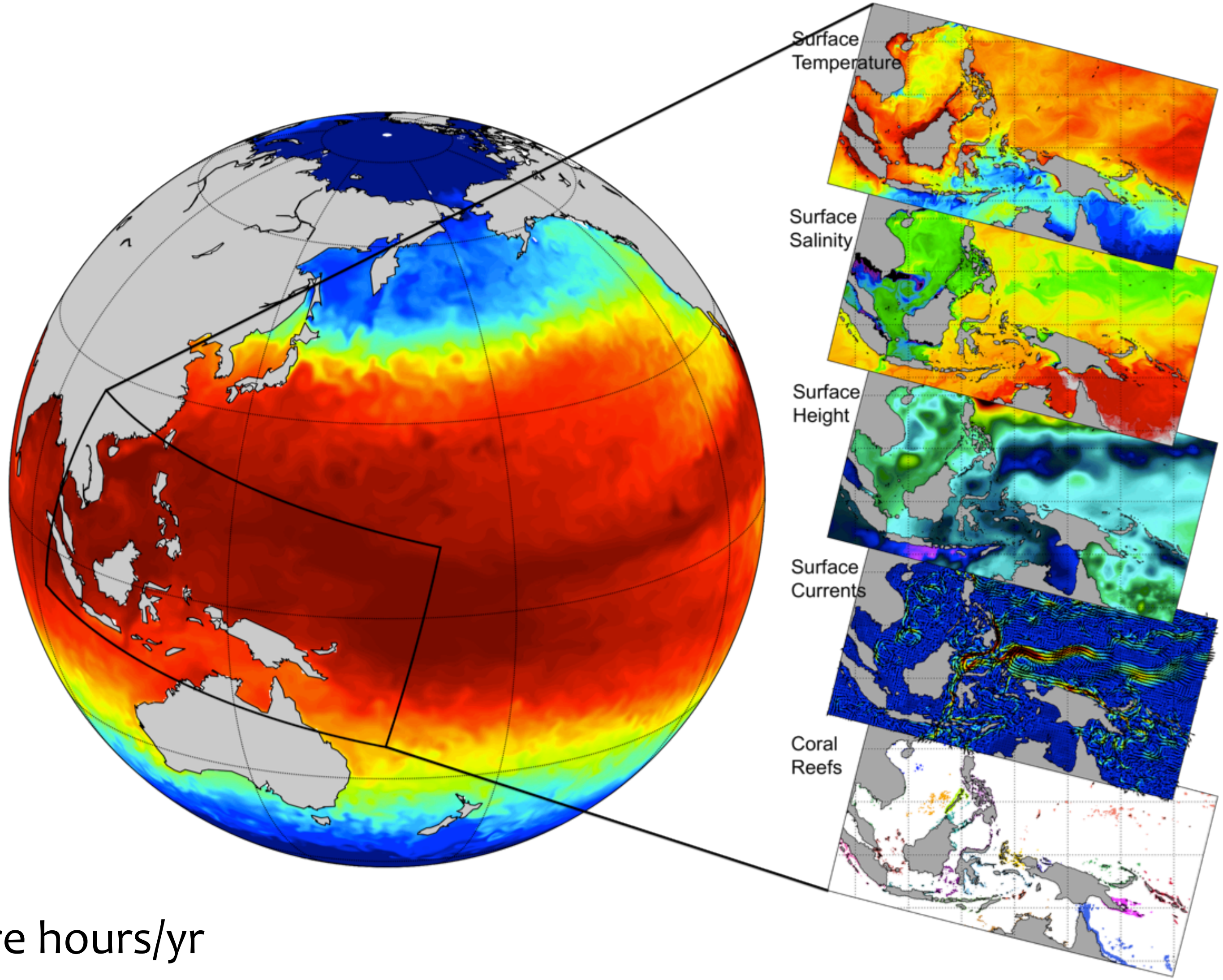
Horizontal res.: *5 km*

Vertical res.: 50 levels

Time step: 90 sec

Boundary cond.:

MERRA, SODA, CESM



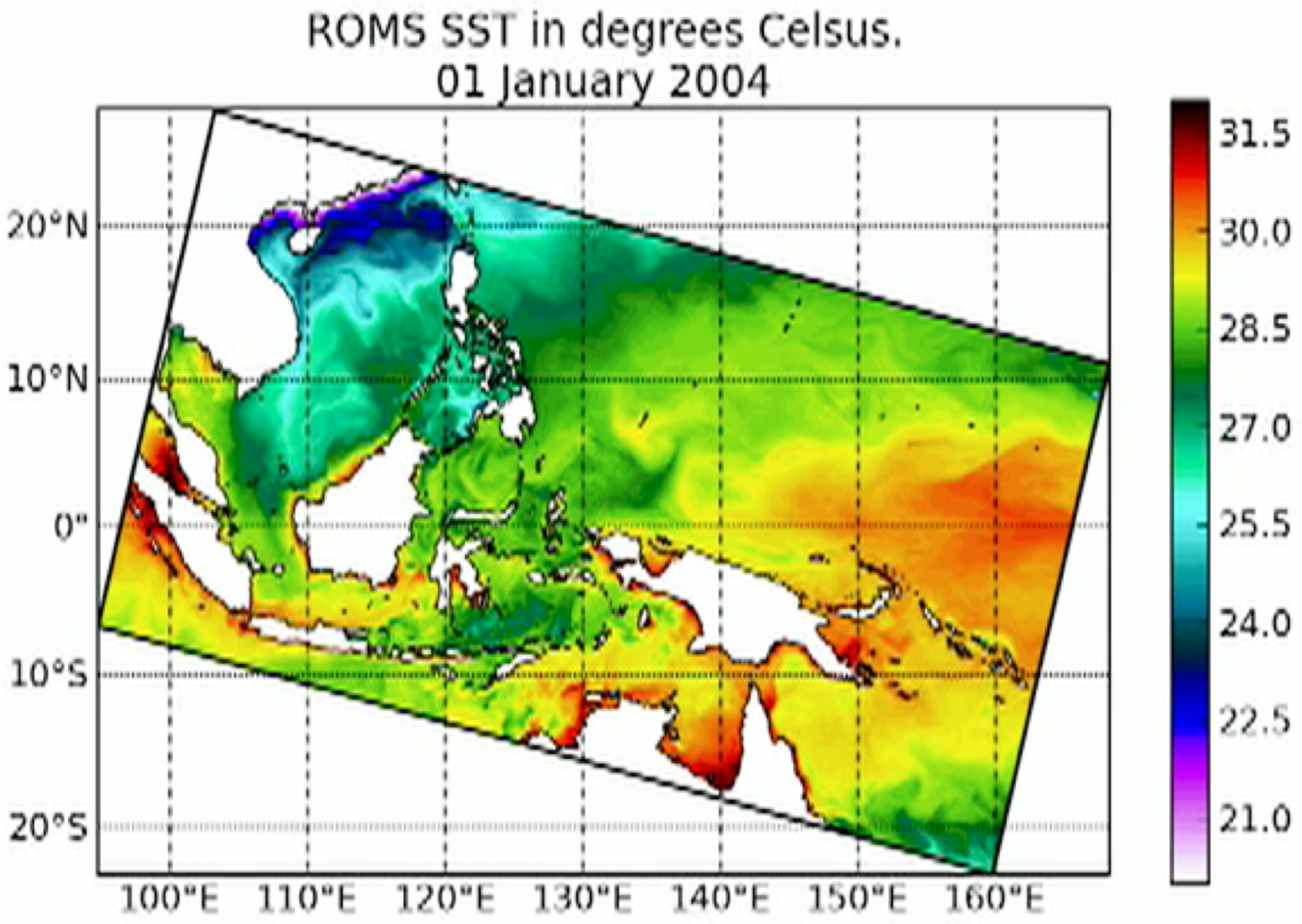
Computation: 40,000 core hours/yr

Data storage: 600 GB/yr (daily averages)

CT-ROMS

Experiments

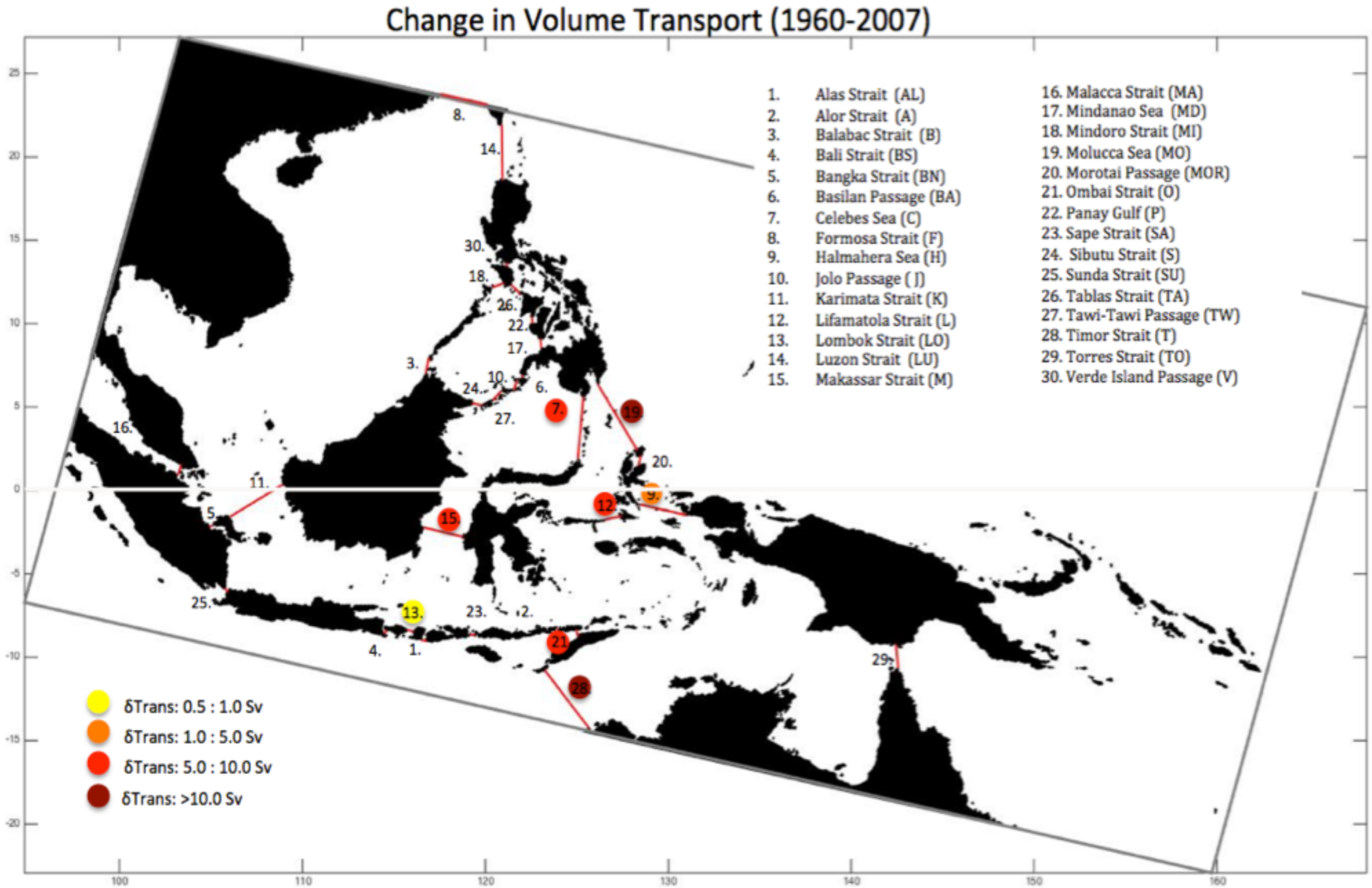
Experiments	Years	Atm. Forcing	Ocean Forcing
Development run	2004–2006	MERRA	SODA
20th Century	1960–2007	CORE2	SODA
21st Century	1960–1979 2040–2059 2080–2099	CESM2 – RCP8.5	CESM2 – RCP8.5
0.5 km Verde I Passage and Camotes Sea	1996–1998	CT-ROMS 5.0 km	CT-ROMS 5.0 km
BGC (w/ COBALT)		CORE2	SODA
Extended 20th Century	1980–2016	CORE2	SODA3



Animation of daily SST, 2004-2006

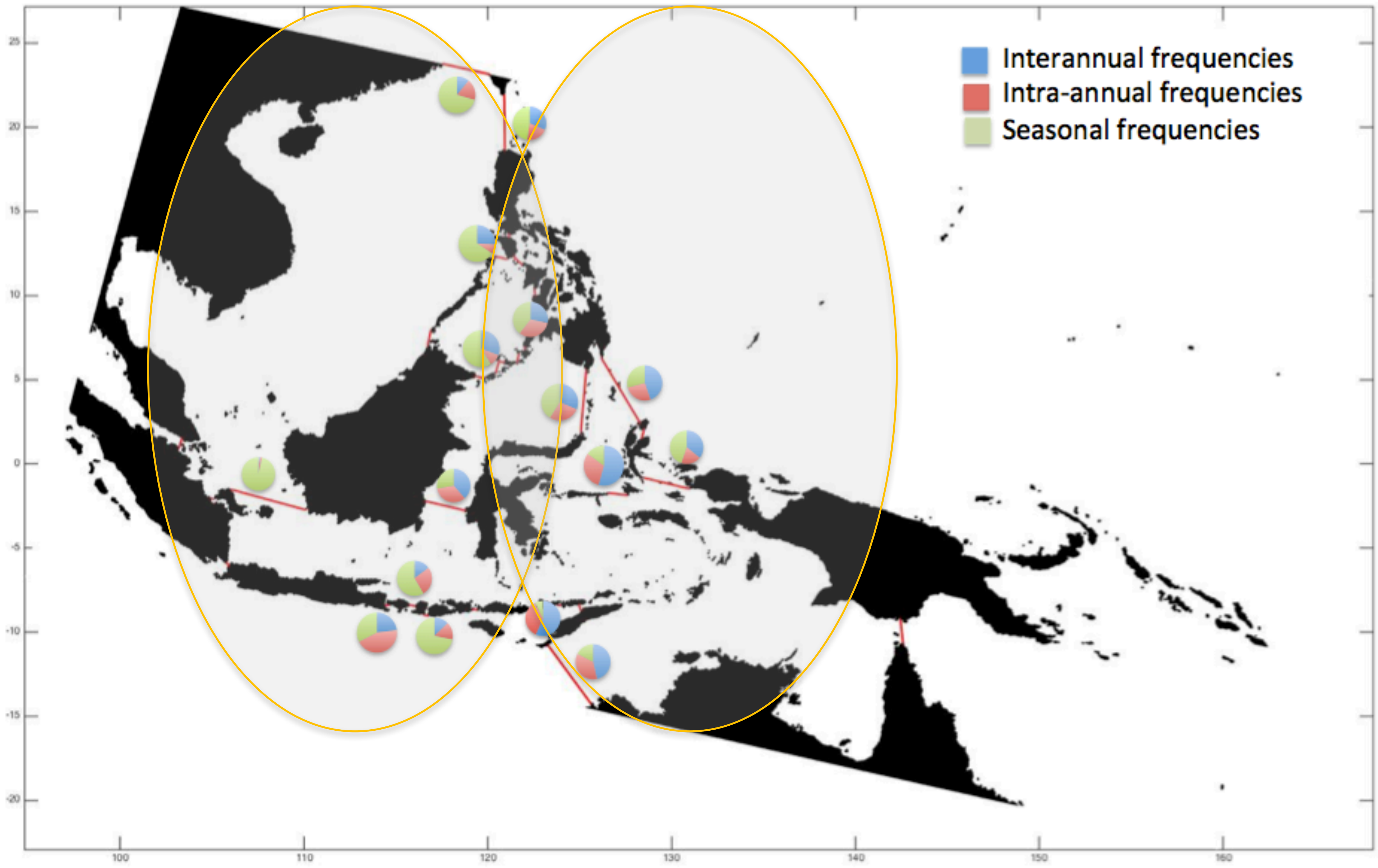
Animation removed for PDF – please see: http://www.ctroms.ucar.edu/animations/daily_SST_ROMS_animation.mp4

Trends in circulation



Lietzke et al., *In prep.*

Attribution of transport variability



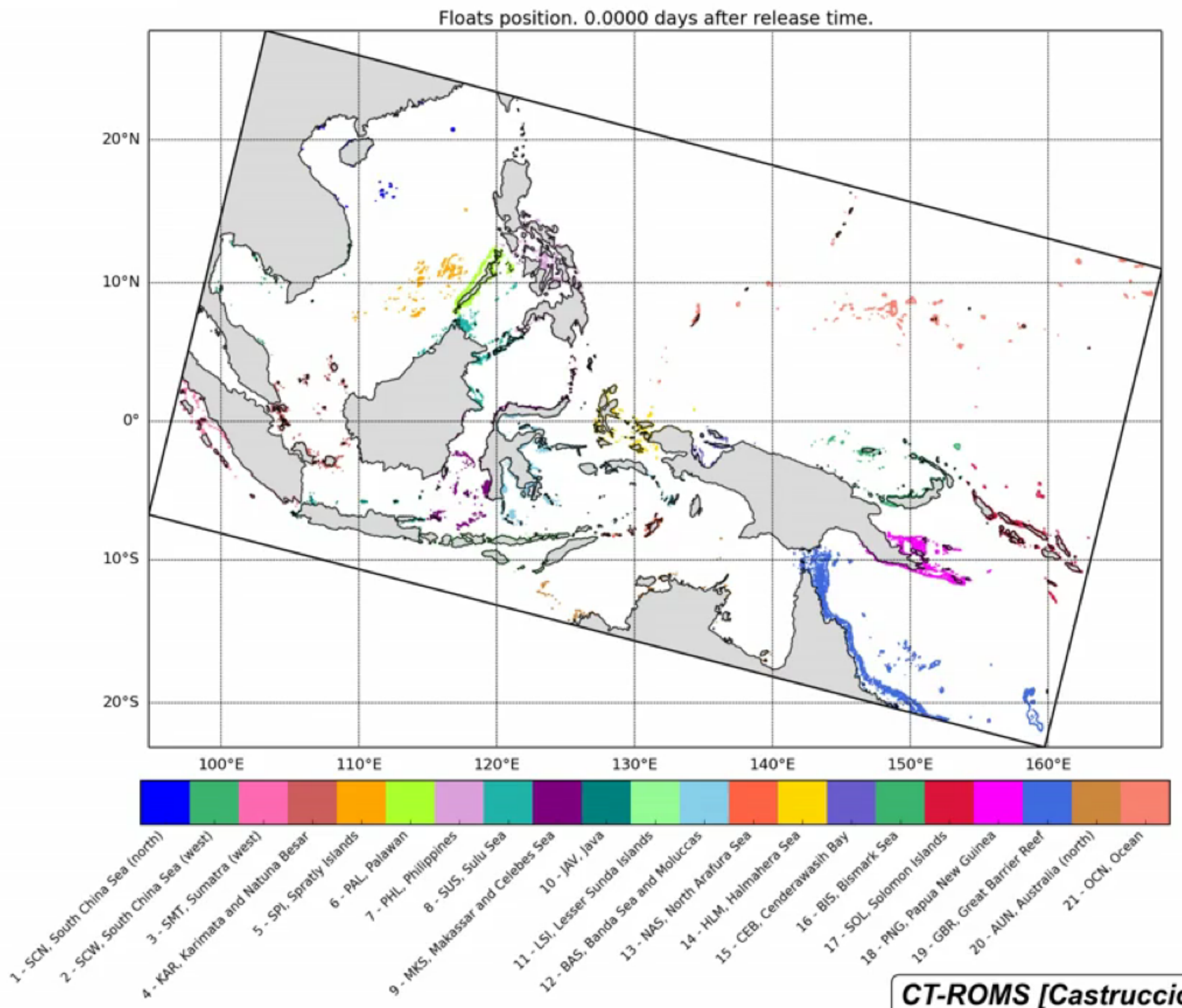
Lietzke et al., *In prep.*

Particle Dispersal

“Coral Connectivity”

Animation of particle tracking in CT-ROMS for 60 days.

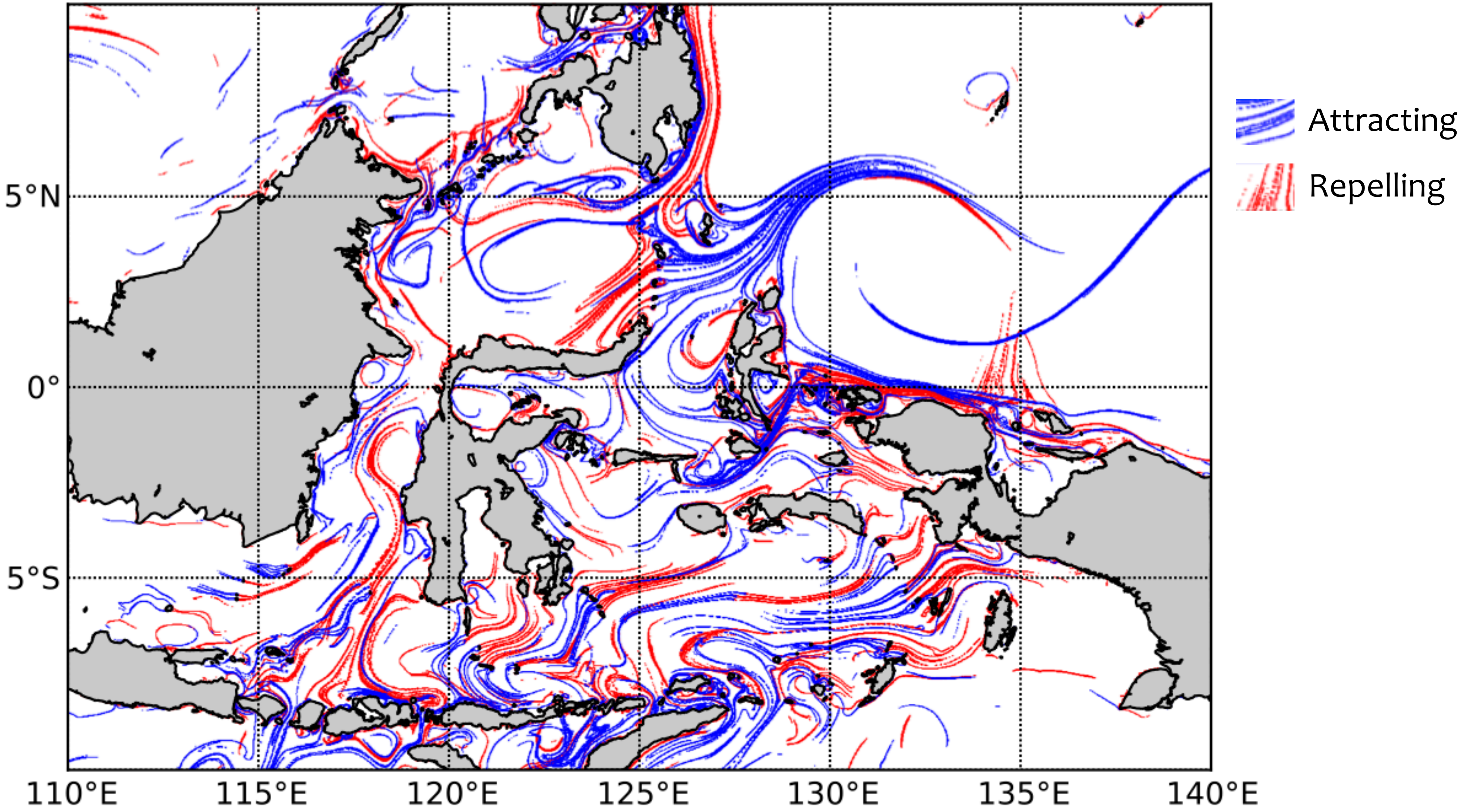
Animation removed for PDF please see: http://www.ctroms.ucar.edu/animations/float_animation.mp4



CT-ROMS [Castruccio et al., 2013].

Lagrangian Coherent Structures

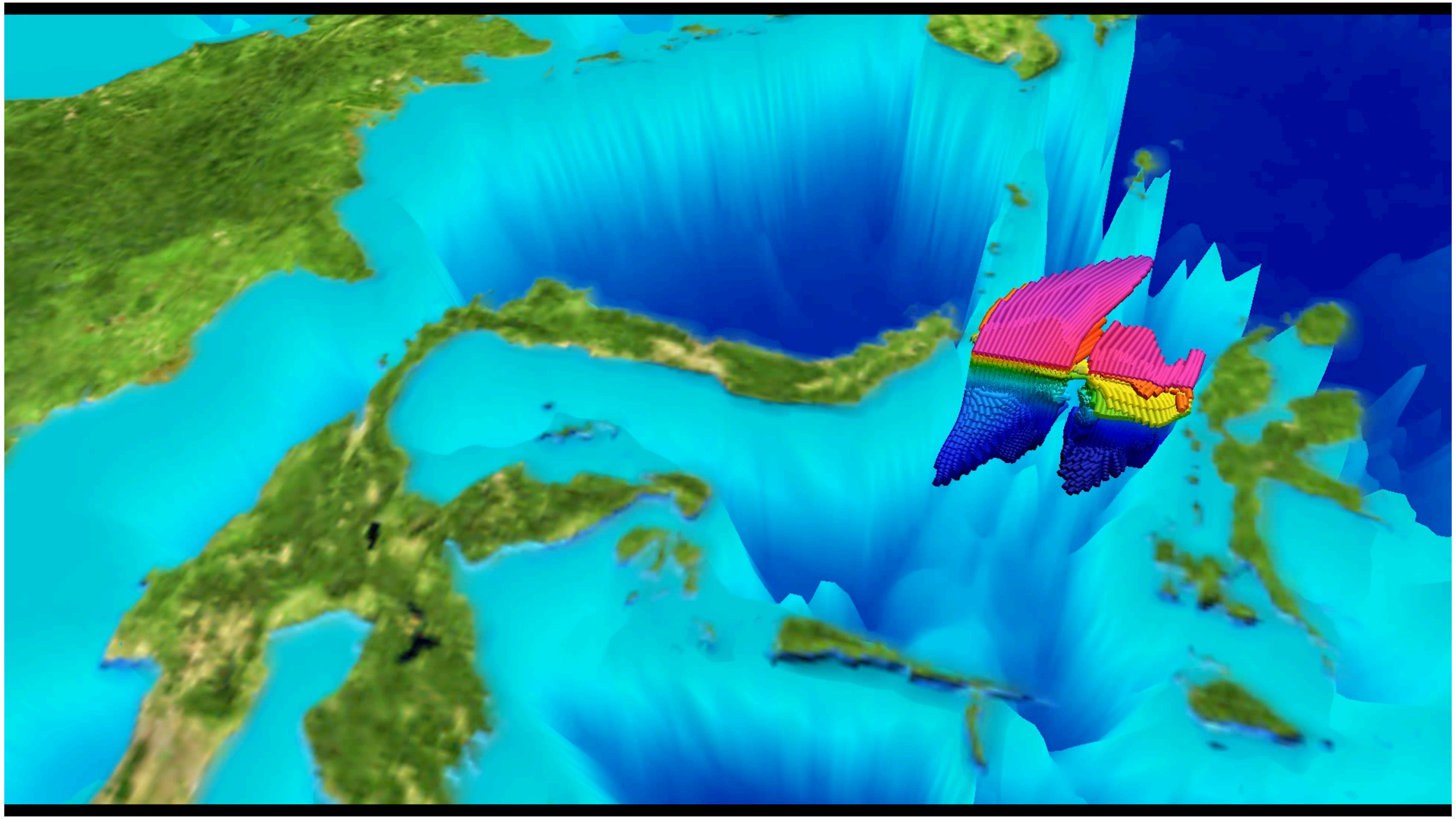
Conduits & Barriers for Transport



Castruccio *et al.*, 2013, *J. Geophys. Res.*

Particle Transport

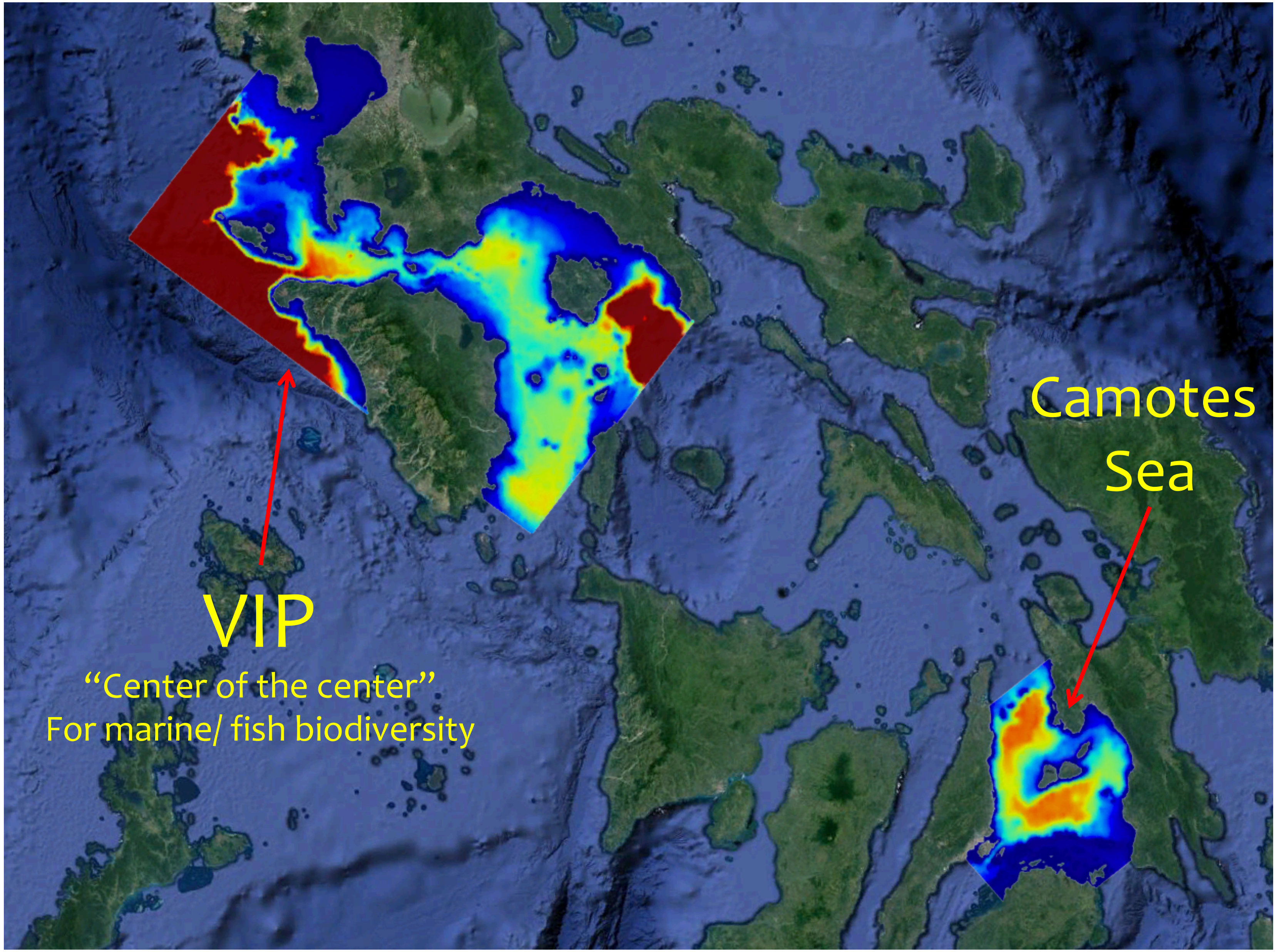
Coral Larval Connectivity



Animation courtesy of Scott Pearse
NCAR Viz Lab

3D Visualization of particle dispersal within Indonesian Throughflow north of Lifamatola Strait
Animation removed for PDF – please see: https://youtu.be/rXKmyyVI0x0

For specific regions: Very high-resolution model domains



VIP Specifications

Horizontal resolution: ~0.5 km

Vertical resolution: 50 layers

Boundary cond.: CT-ROMS

Time frame: 1996-1998

Drenkard et al., *In prep.*

High-resolution ROMS model of Verde Island Passage

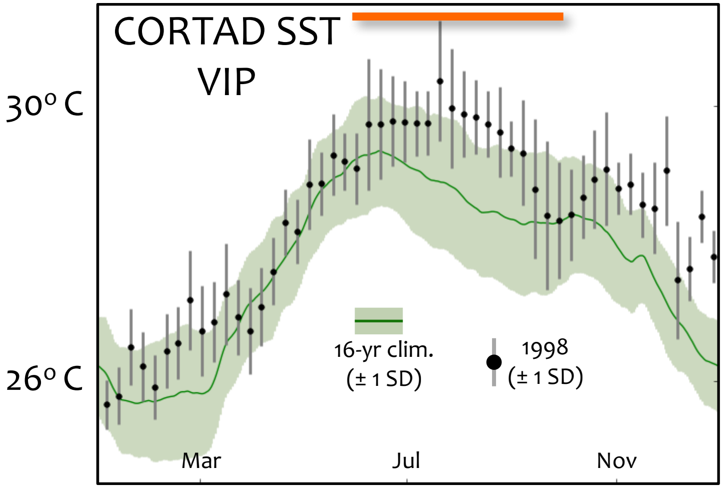
NCAR

Objective

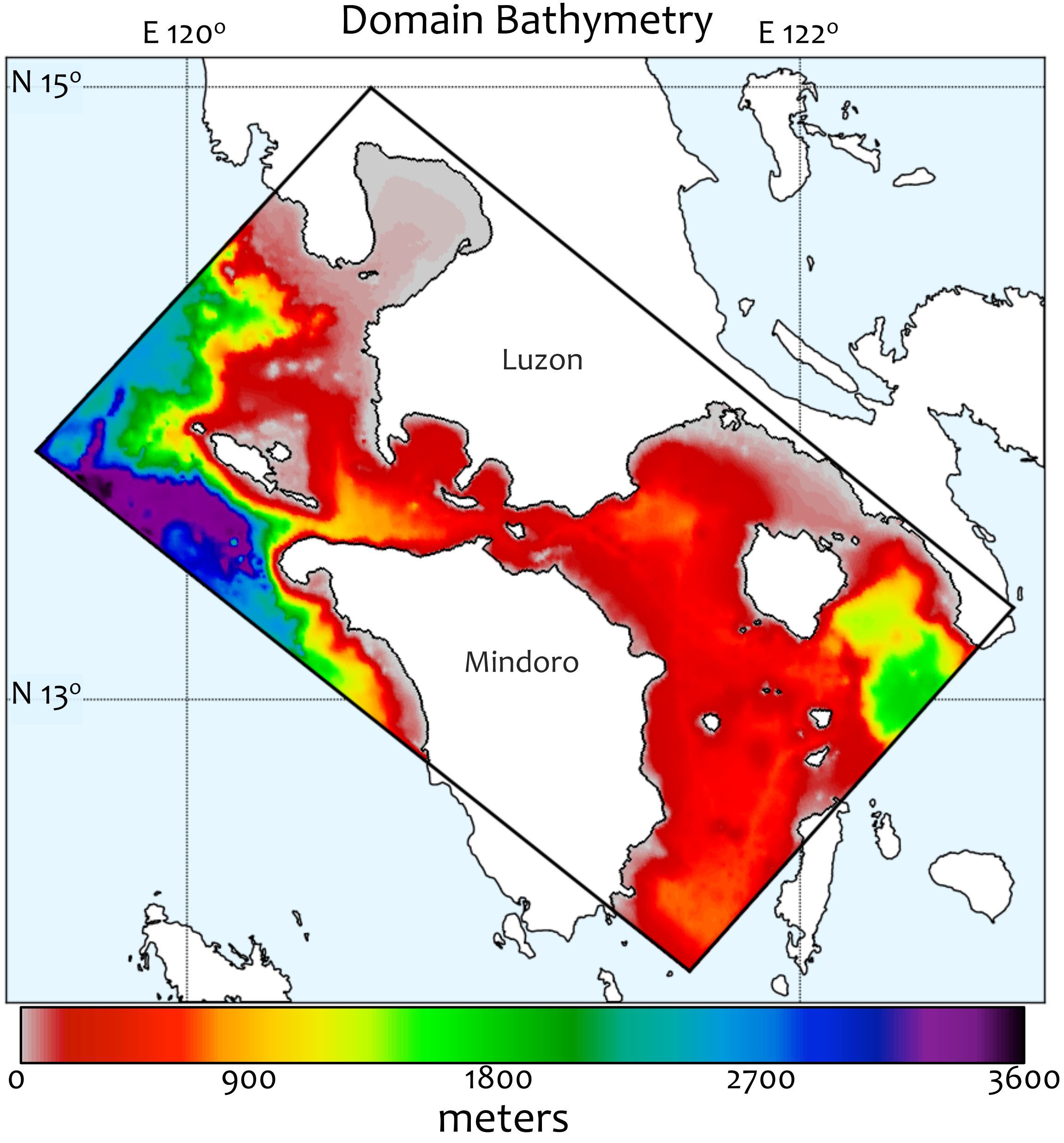
What ocean mechanisms modulated VIP SST in 1998?

Model specifications

- ~500m resolution; 50 layers
- Time frame: 1996-1999
- Atmospheric Forcing: MERRA
- Boundary Conditions: CT-ROMS
- Rivers and Tides



Domain Bathymetry

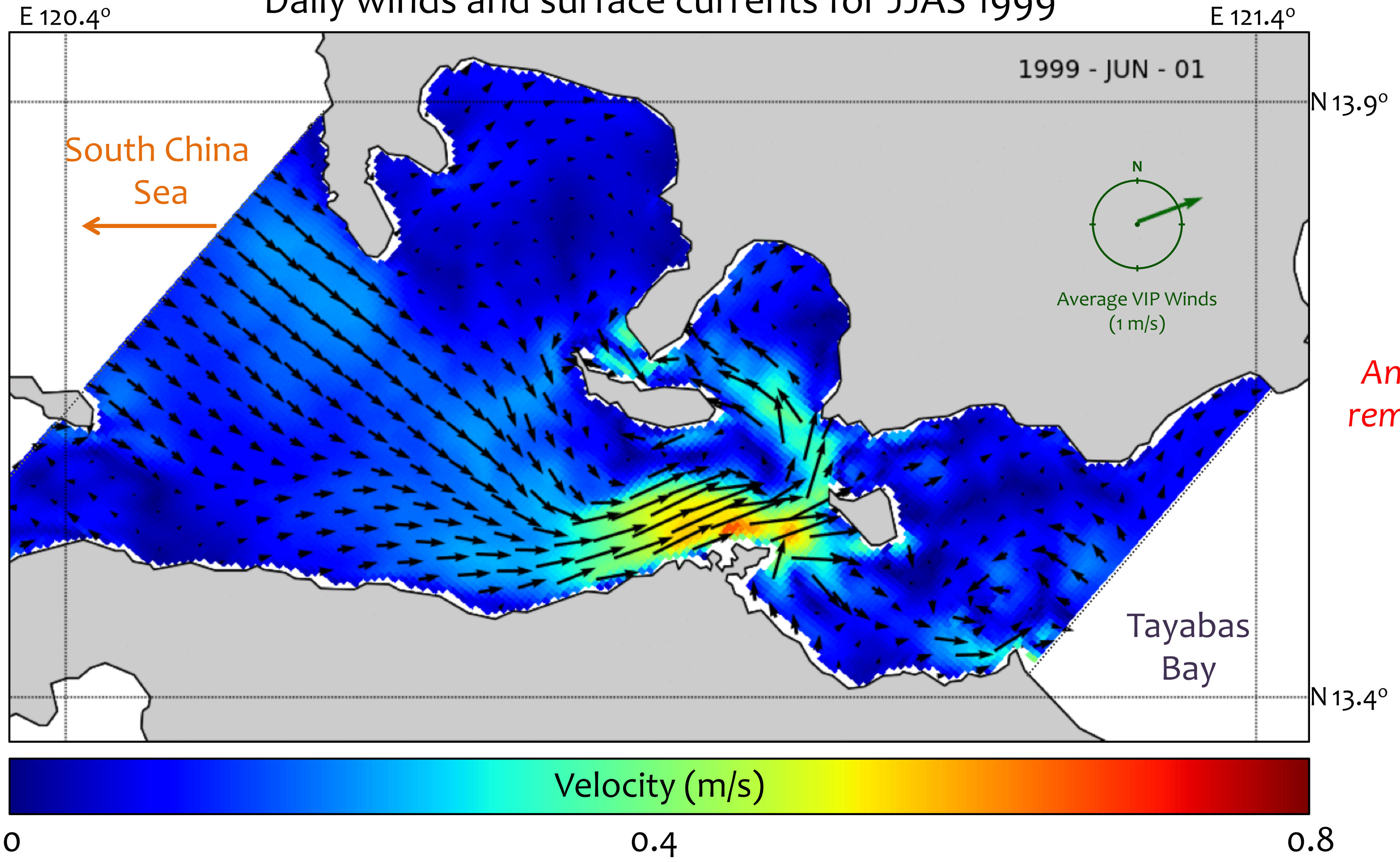


General VIP Dynamics:

Winds directly influence surface currents

Highly dynamic region with rapidly reversing surface currents

Daily winds and surface currents for JJAS 1999



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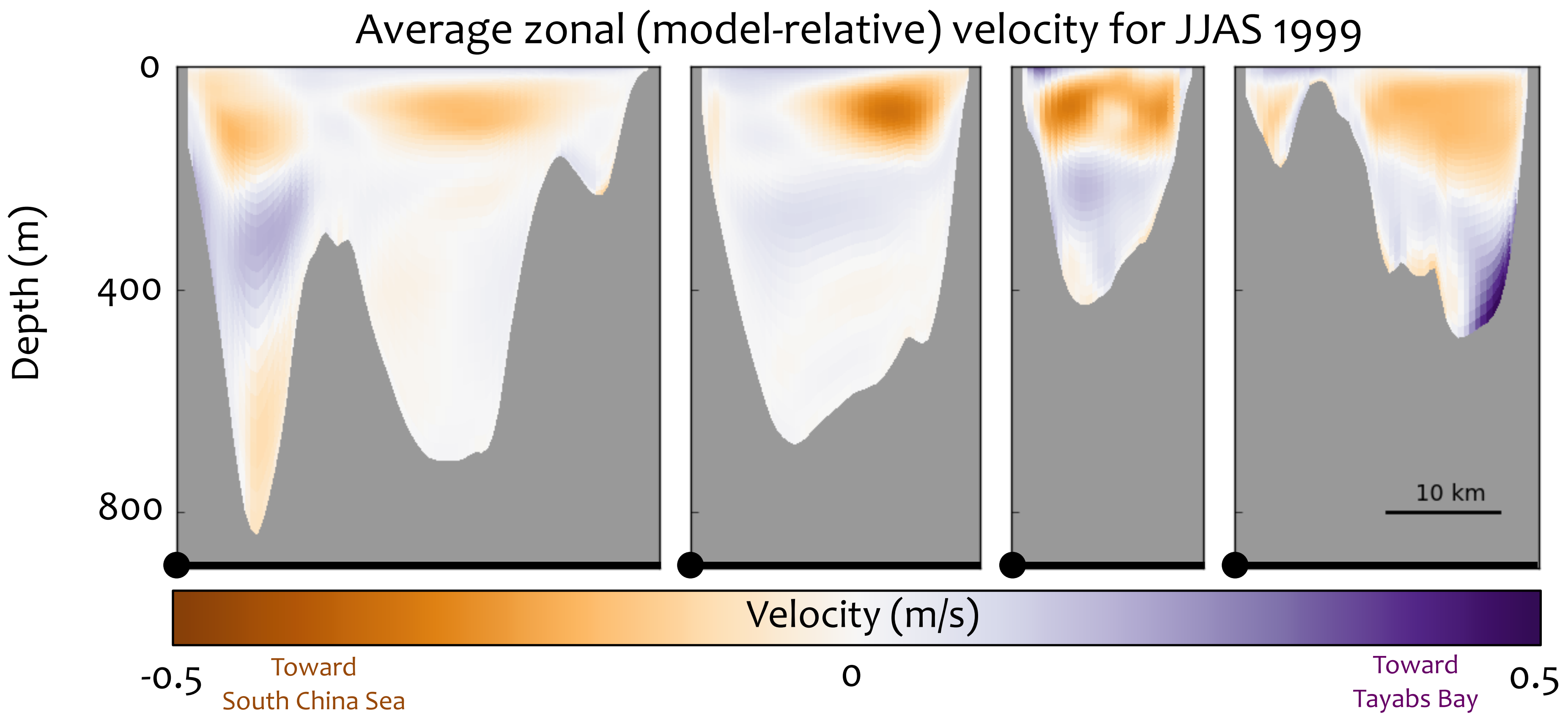
General VIP Dynamics:

SSH gradient drives upper transport



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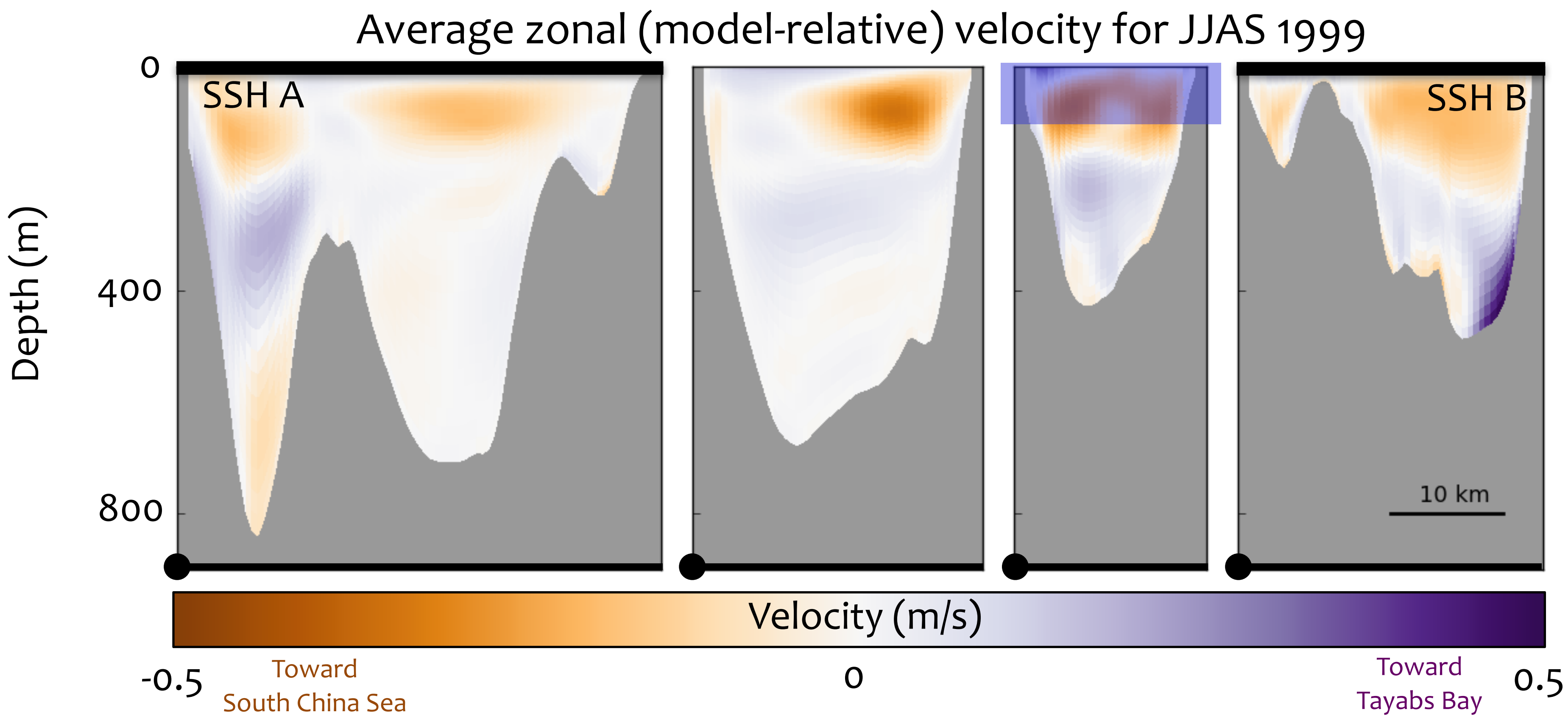

General VIP Dynamics:

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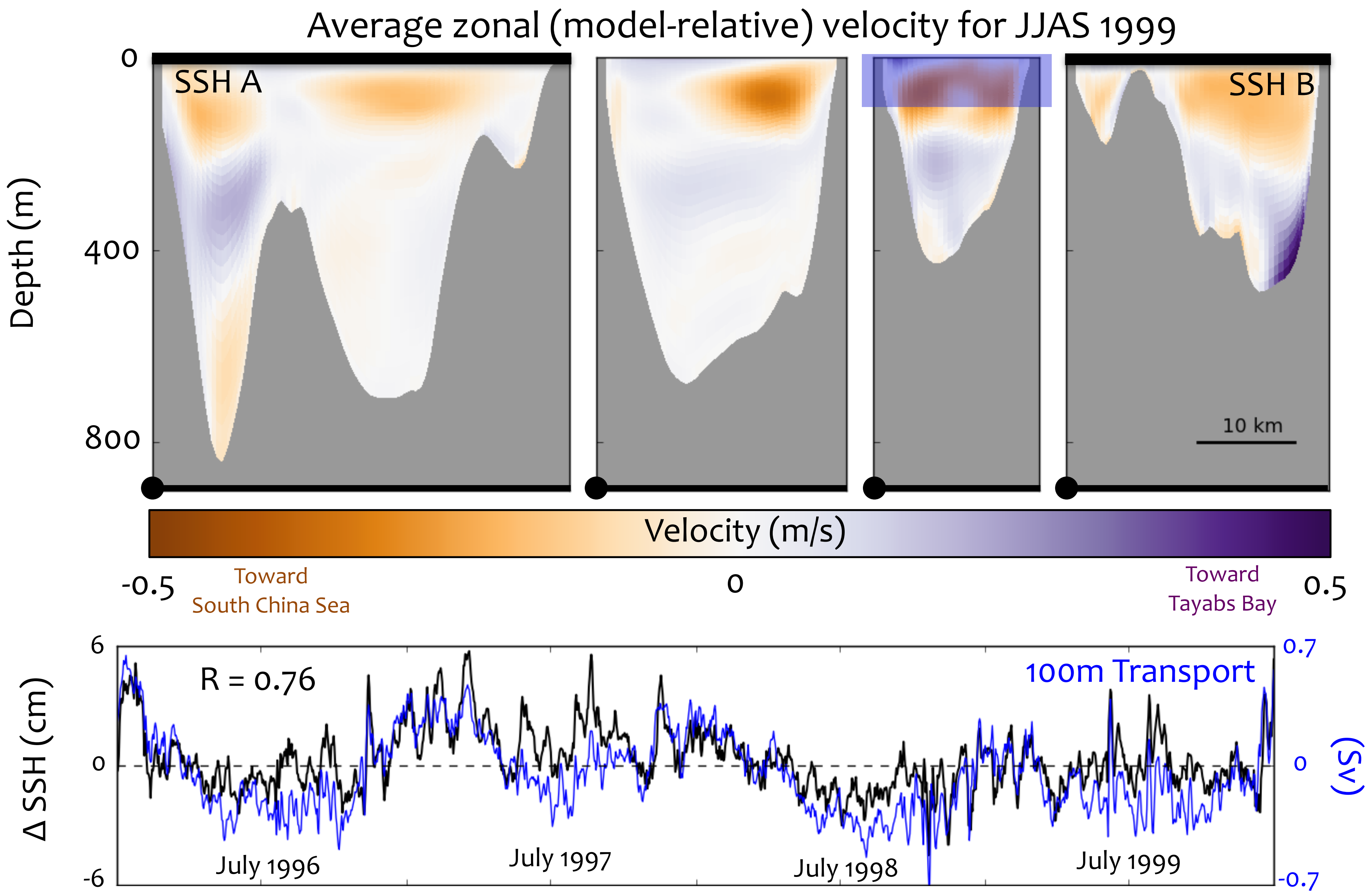
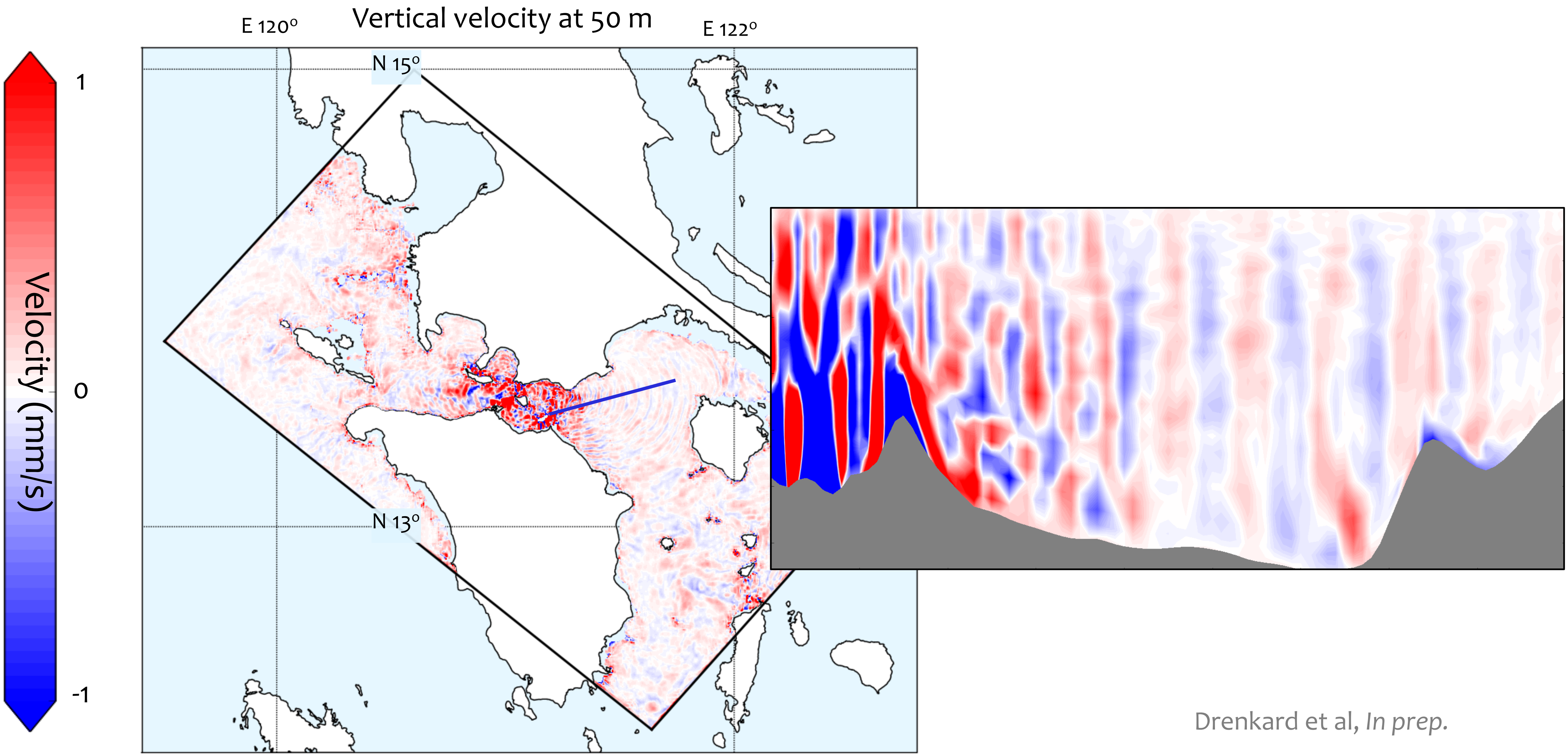


The role of internal tides

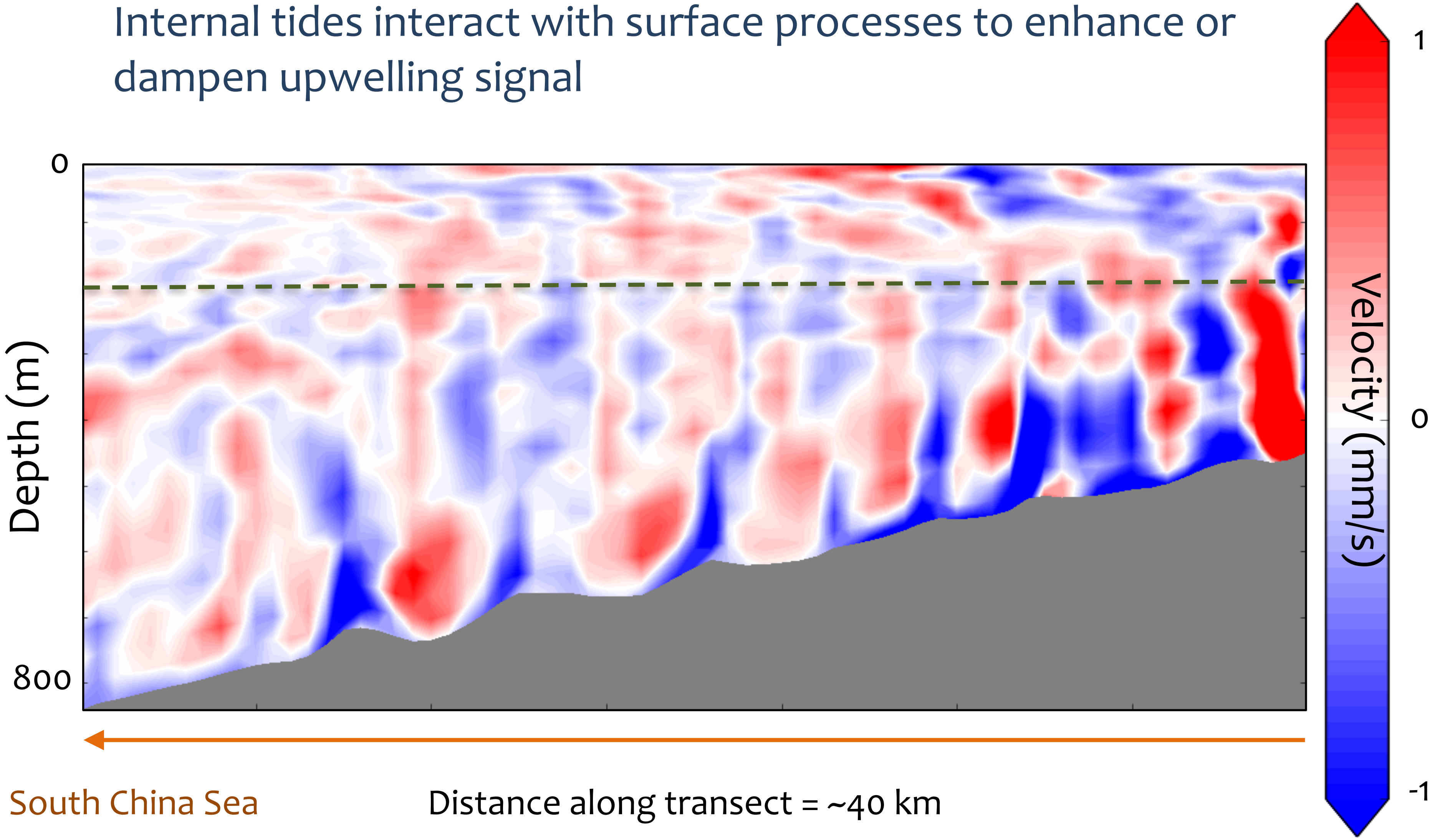


Drenkard et al, *In prep.*

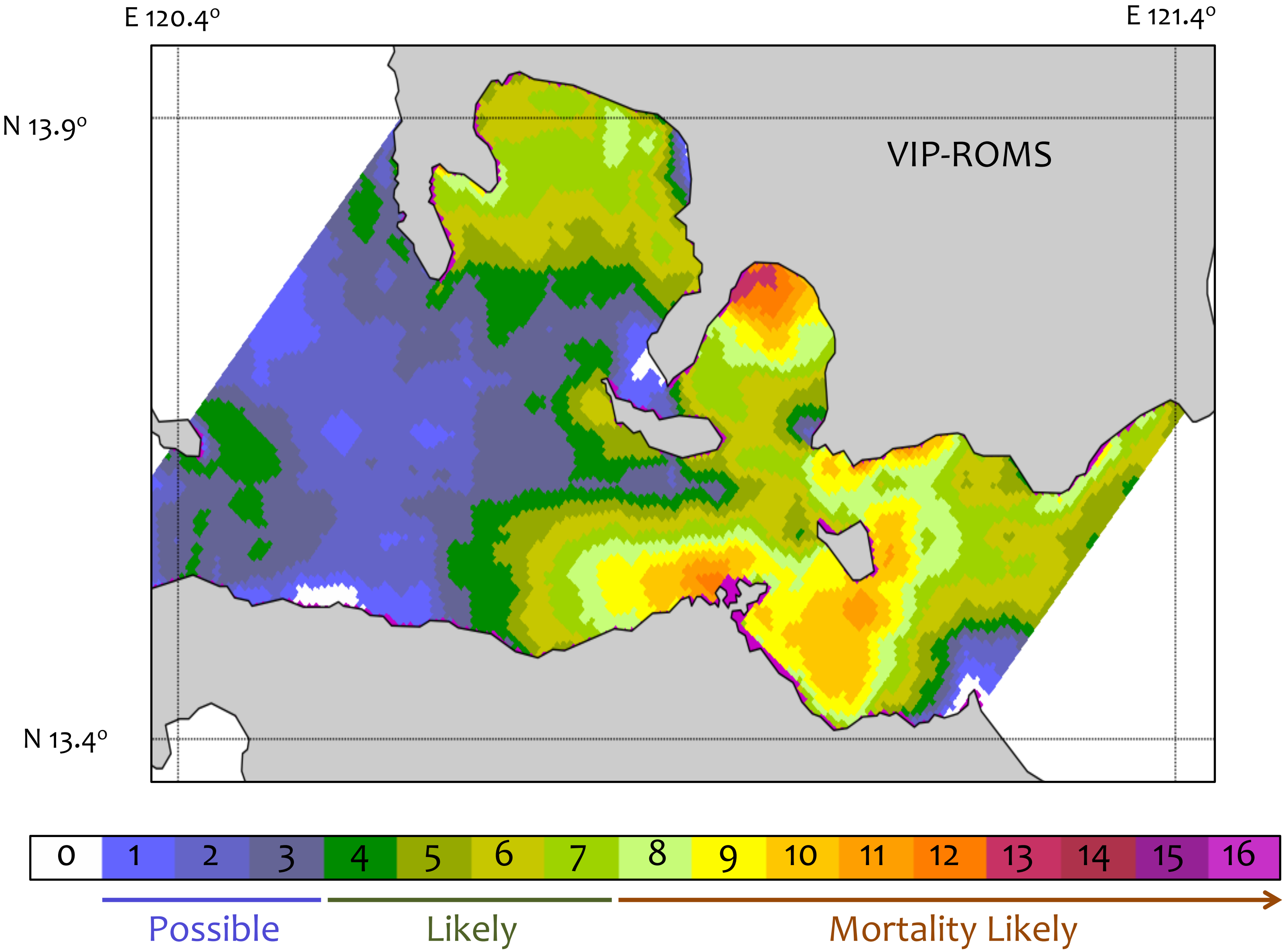
Resolving internal tides:

ITs increase mixing and deliver cold water from depth

Internal tides interact with surface processes to enhance or dampen upwelling signal



Maximum degree heating weeks for 1998



Model resolves spatial heterogeneity in maximum DHW signal

Drenkard et al, *In prep.*

Conservation in the Coral Triangle

Modeling to understand …

Temperature

- Past patterns
- Future projections

Connectivity

- Sources & sinks
- Populations
- Future changes?

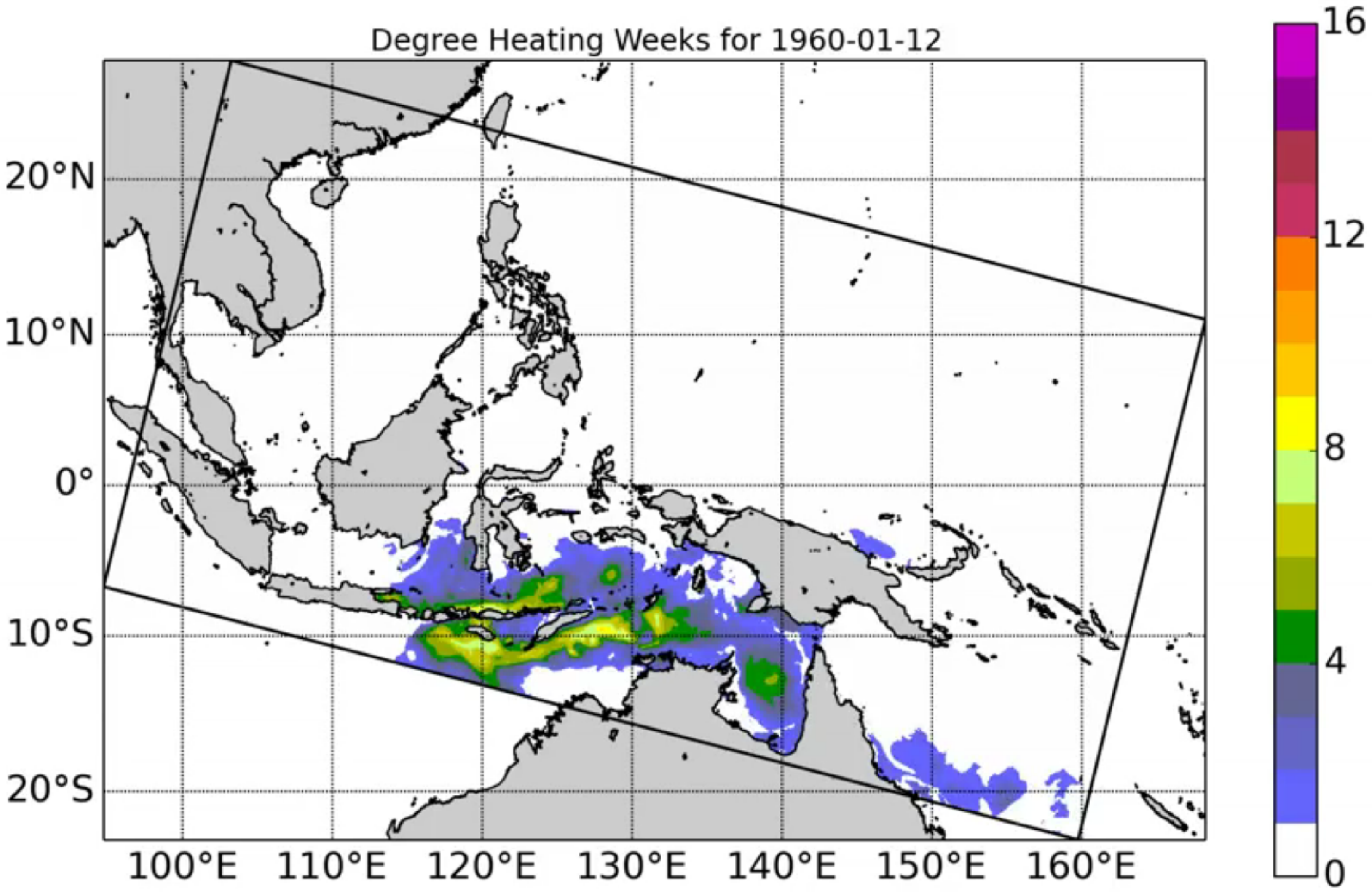
In progress

- Biogeochemistry
  - Carbonate chemistry
  - Productivity
- Population Dynamics

CAN WE IDENTIFY CLIMATE REFUGIA FOR CORAL REEFS?

Less bleaching – Faster recovery – Higher connectivity

CT-ROMS: Degree-Heating-Weeks (DHW)

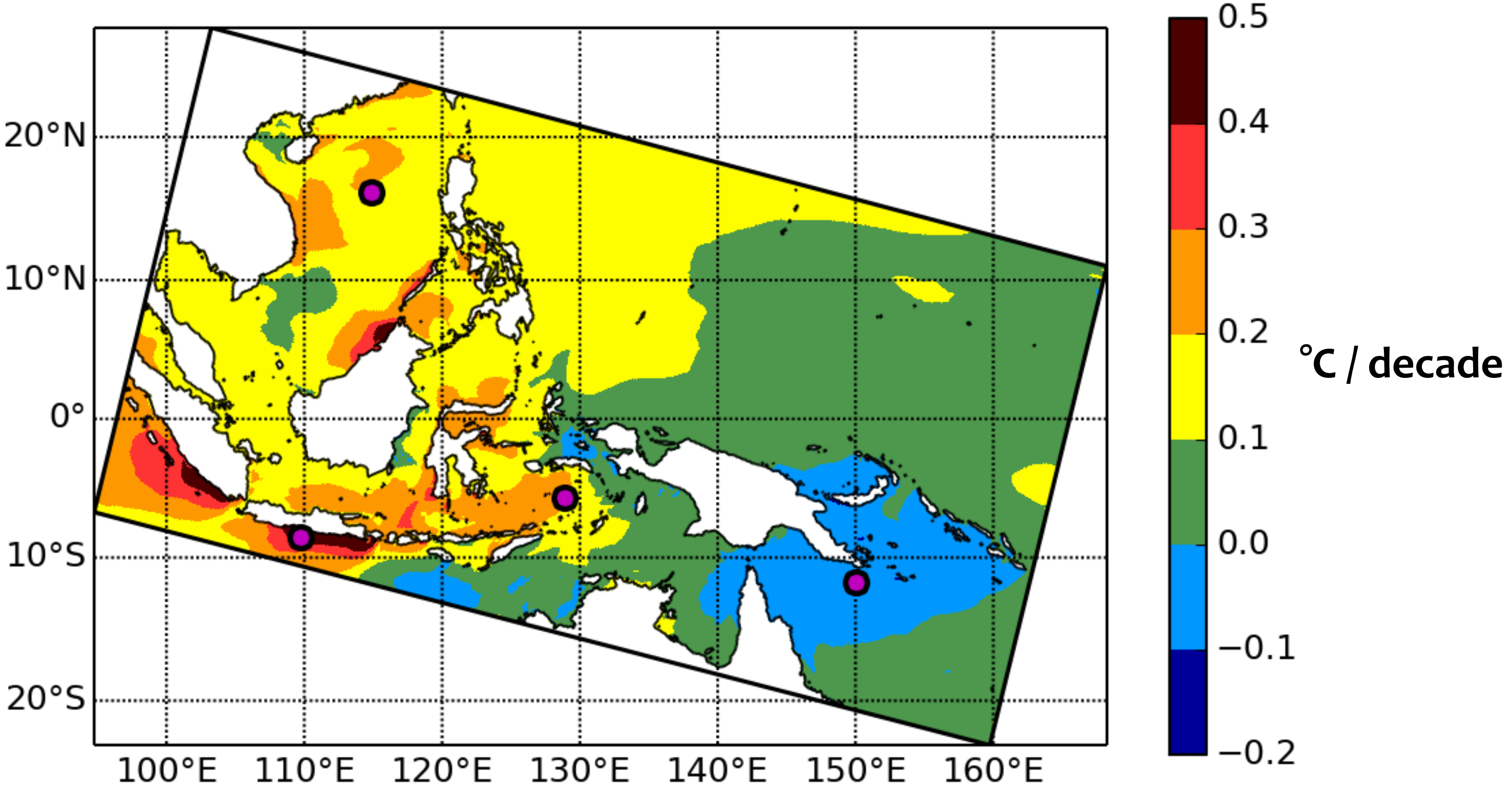


Animation of DHW, 1960-2005

Animation removed for PDF – please see: http://www.ctroms.ucar.edu/animations/DHW_method_2_animation.mp4

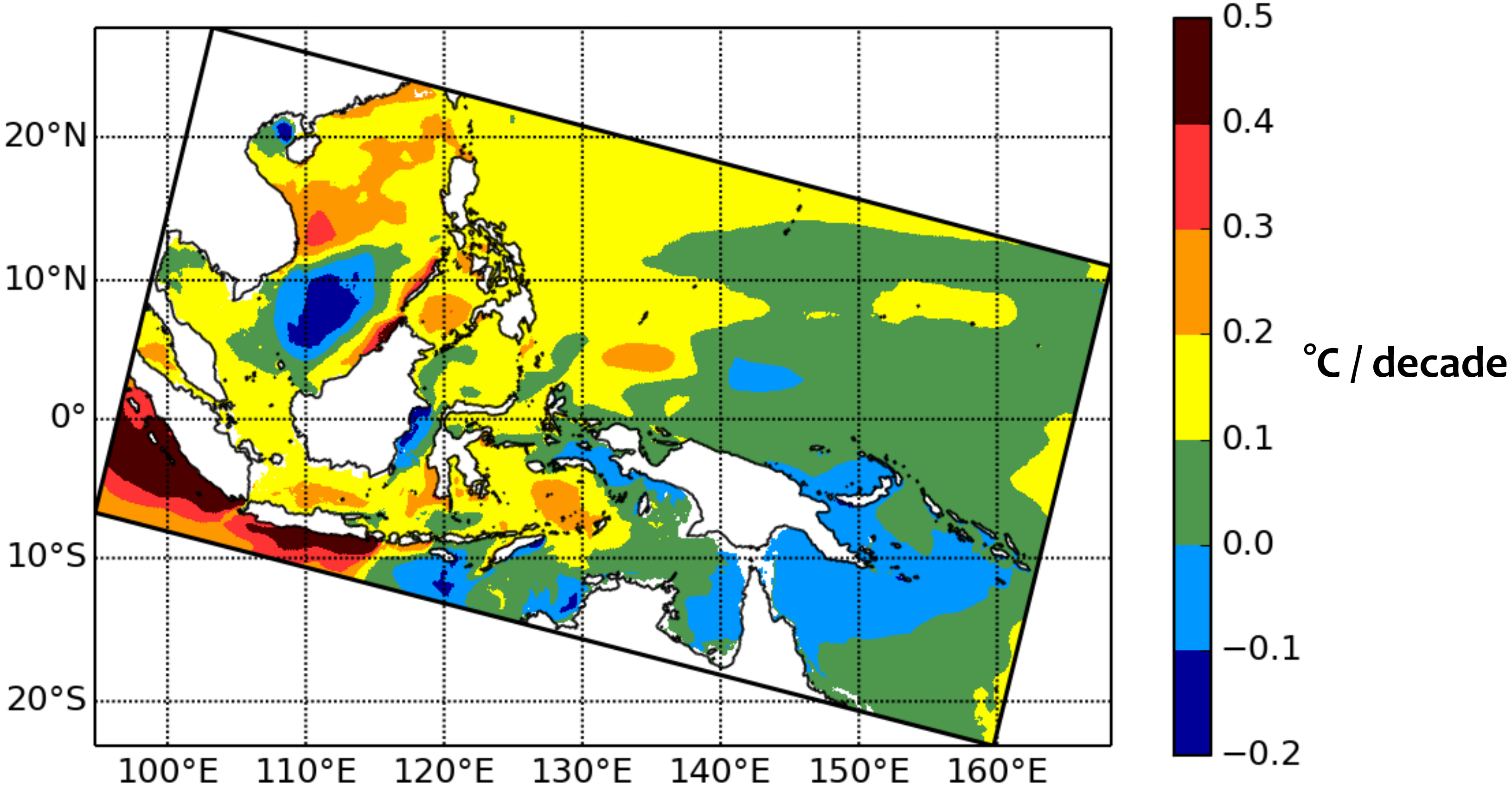
Warming Trend: 1960-2008

Surface



Warming Trend: 1960-2008

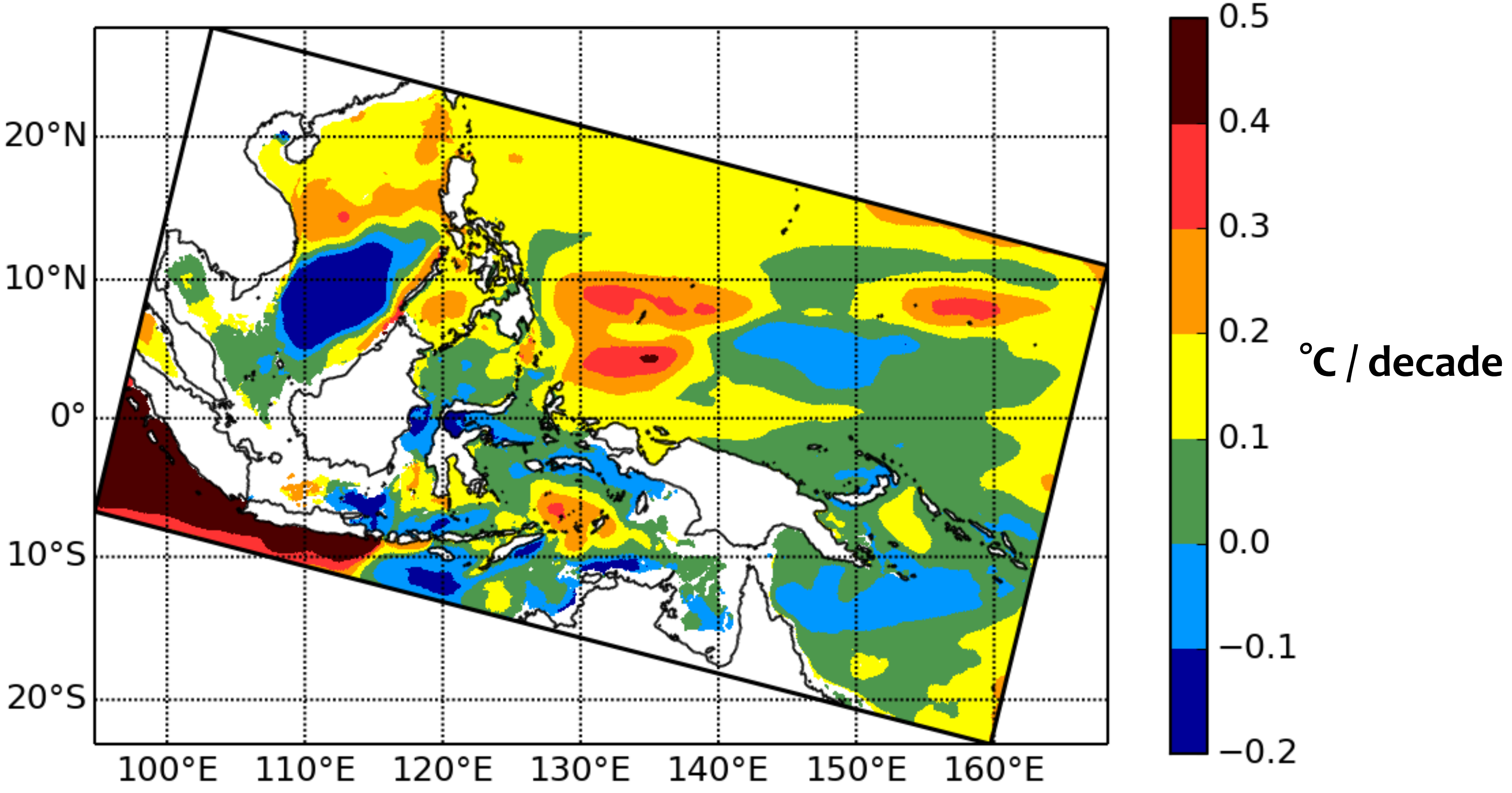
20 m depth



Refugia at depth?

Warming Trend: 1960-2008

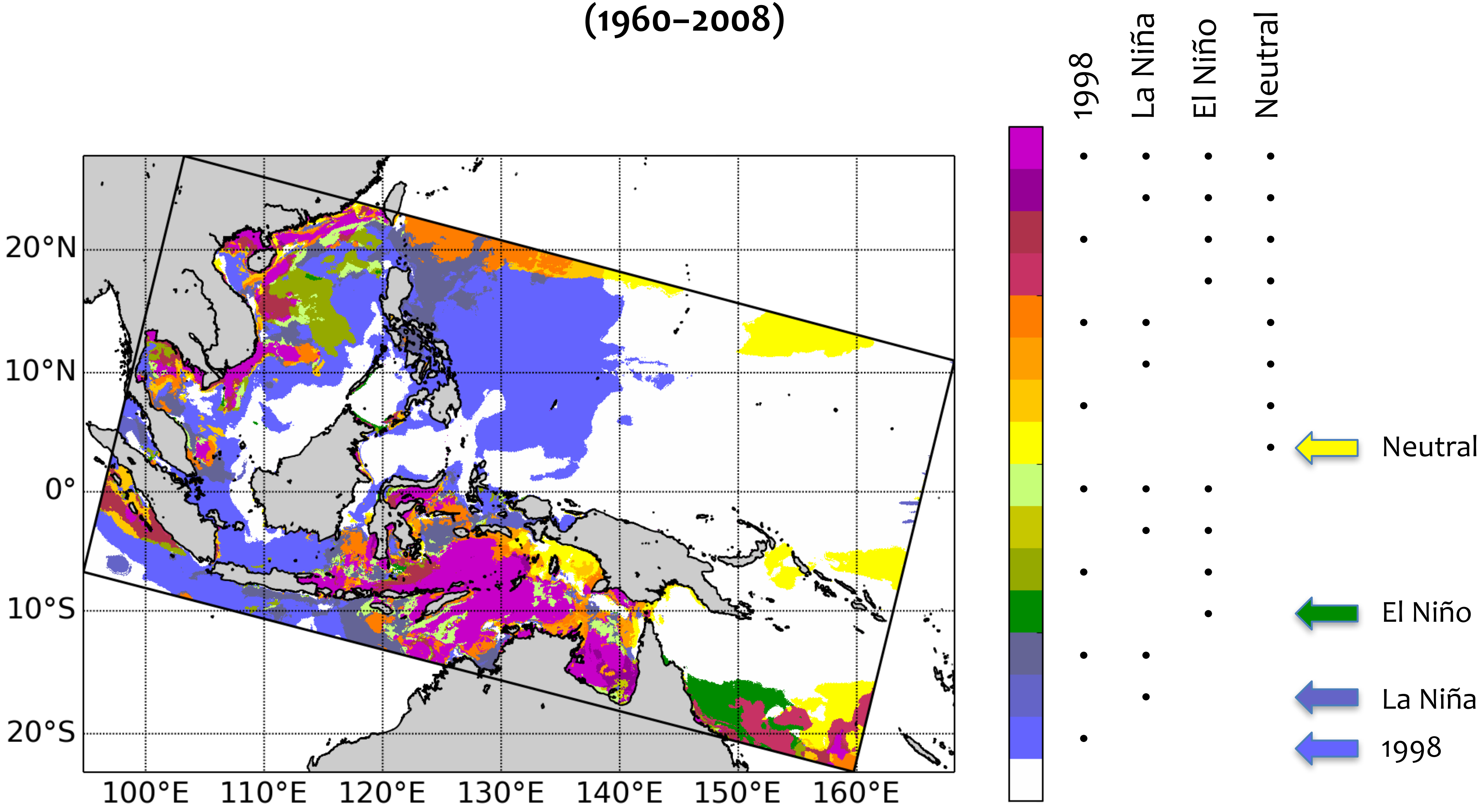
50 m depth



Refugia at depth?

Regions of low heat stress refugia?

(1960–2008)

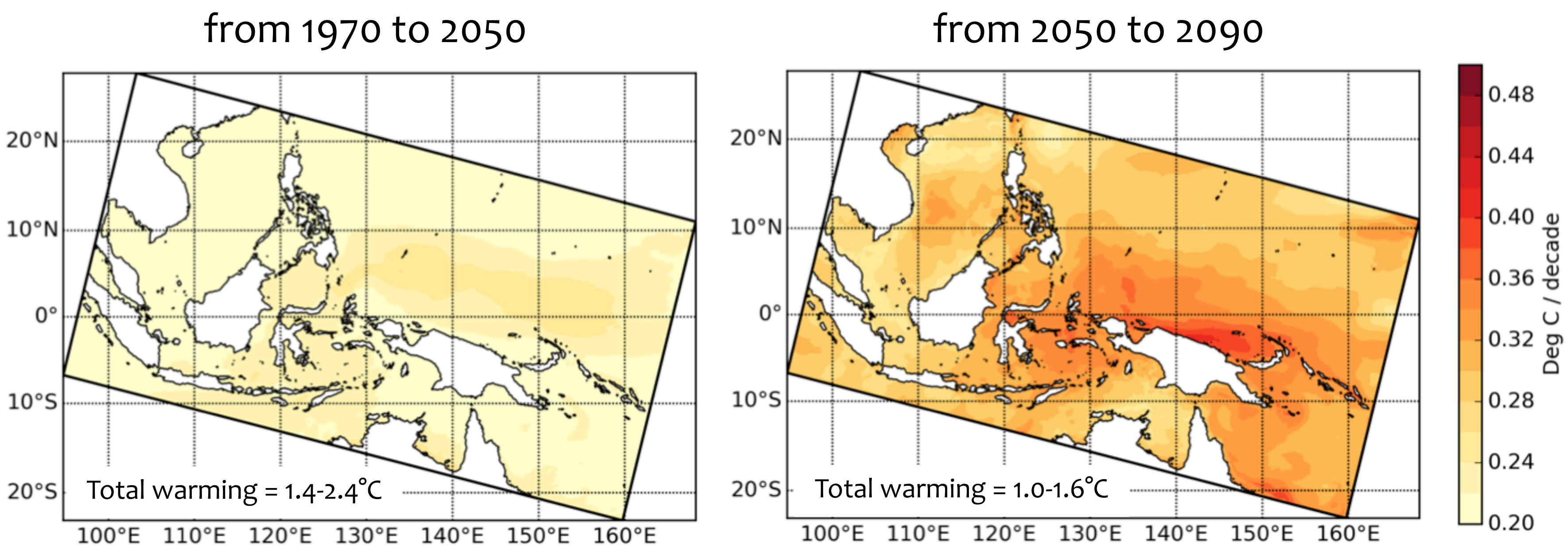


Kleypas et al. 2015 *GCB*

Future rate of warming in the Coral Triangle

High emissions scenario (CESM RCP 8.5)

Rate of warming (°C per decade)

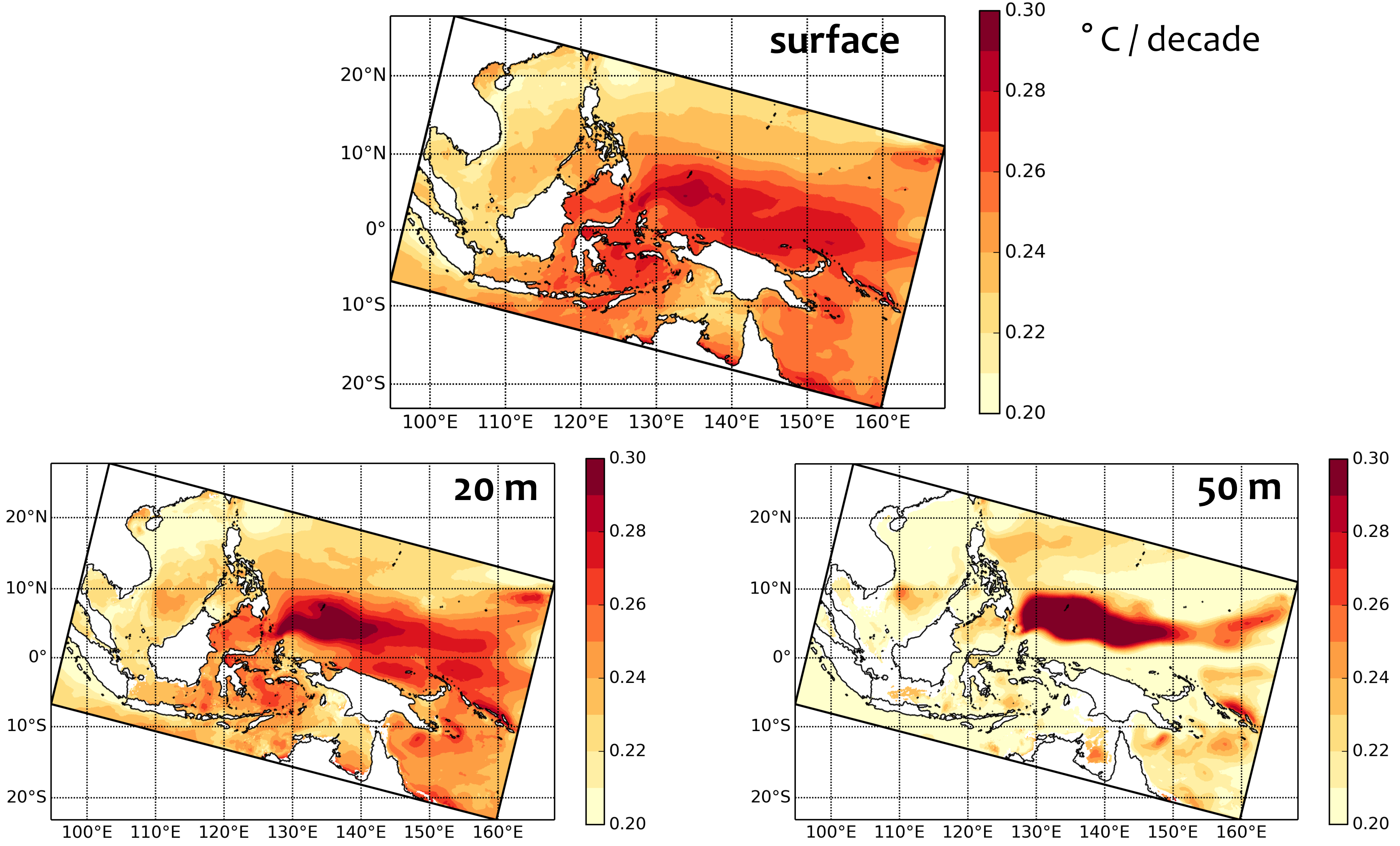


Note the spatial variability in the warming

Kleypas et al. in prep.

A century of warming with depth

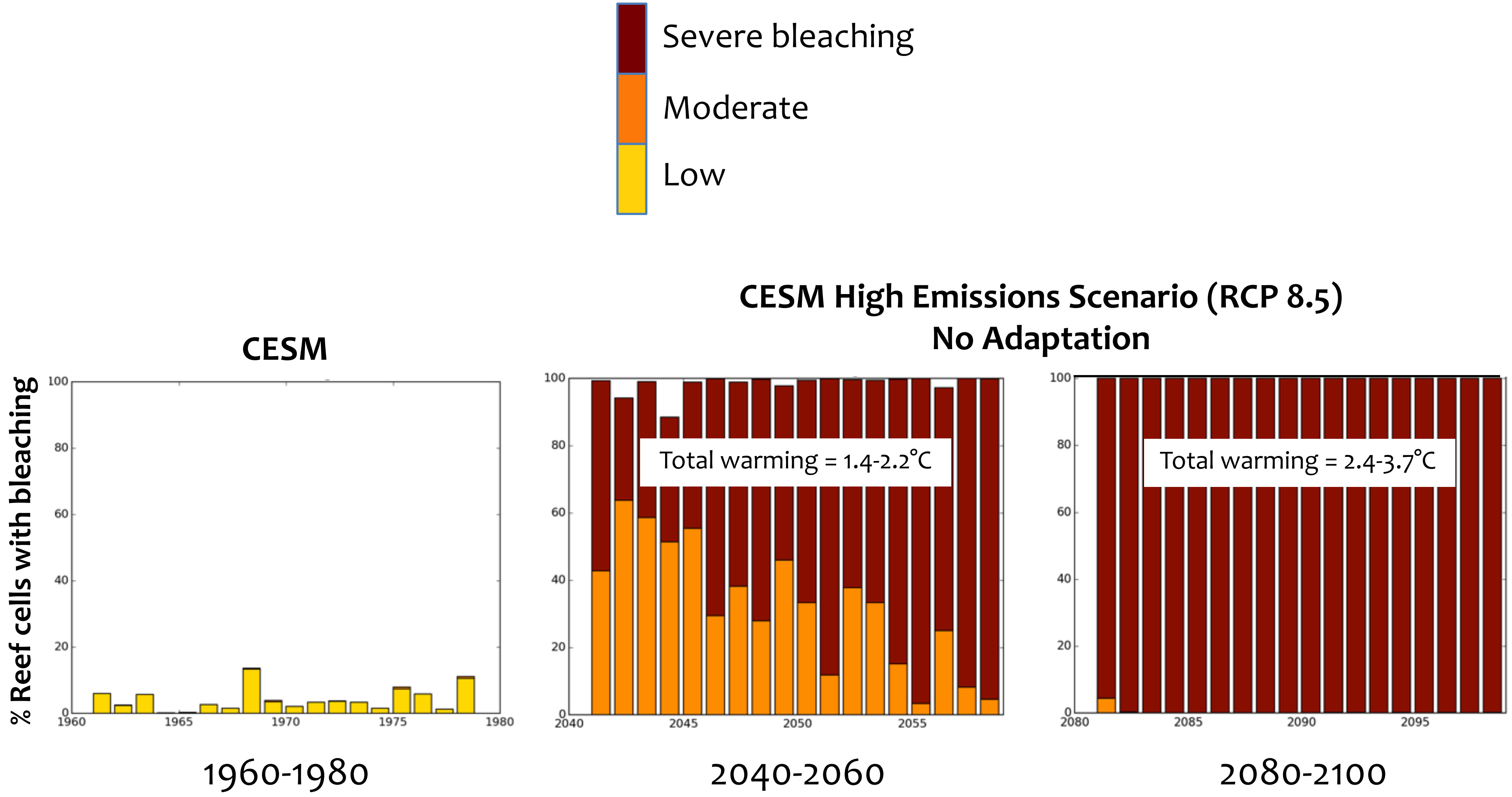
1960-1979 to 2080-2099



Kleypas et al. in prep.

Future Bleaching in the Coral Triangle

High emissions scenario (RCP 8.5)



Kleypas et al. in prep.

Future Bleaching in the Coral Triangle

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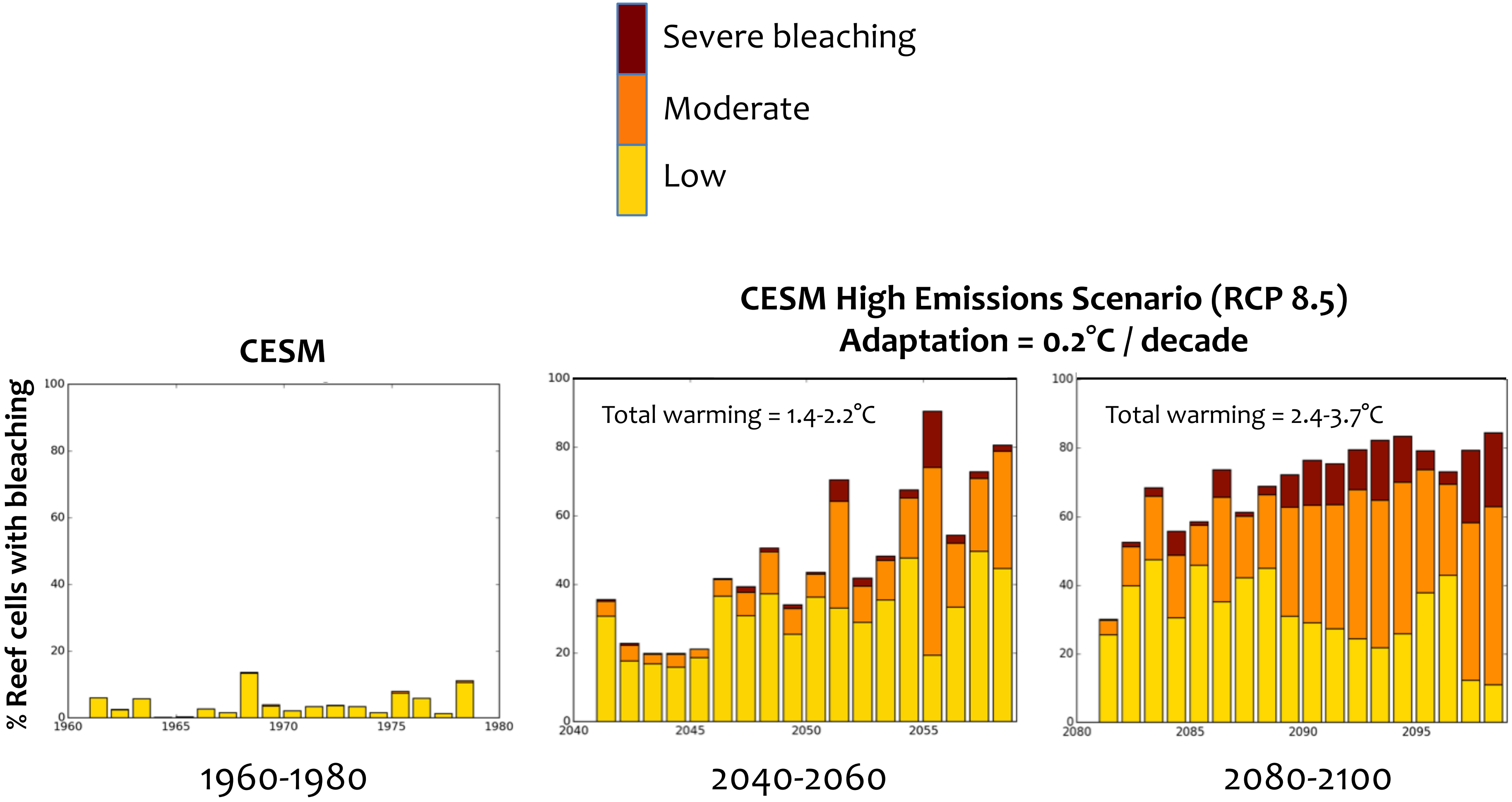


Kleypas et al. in prep.

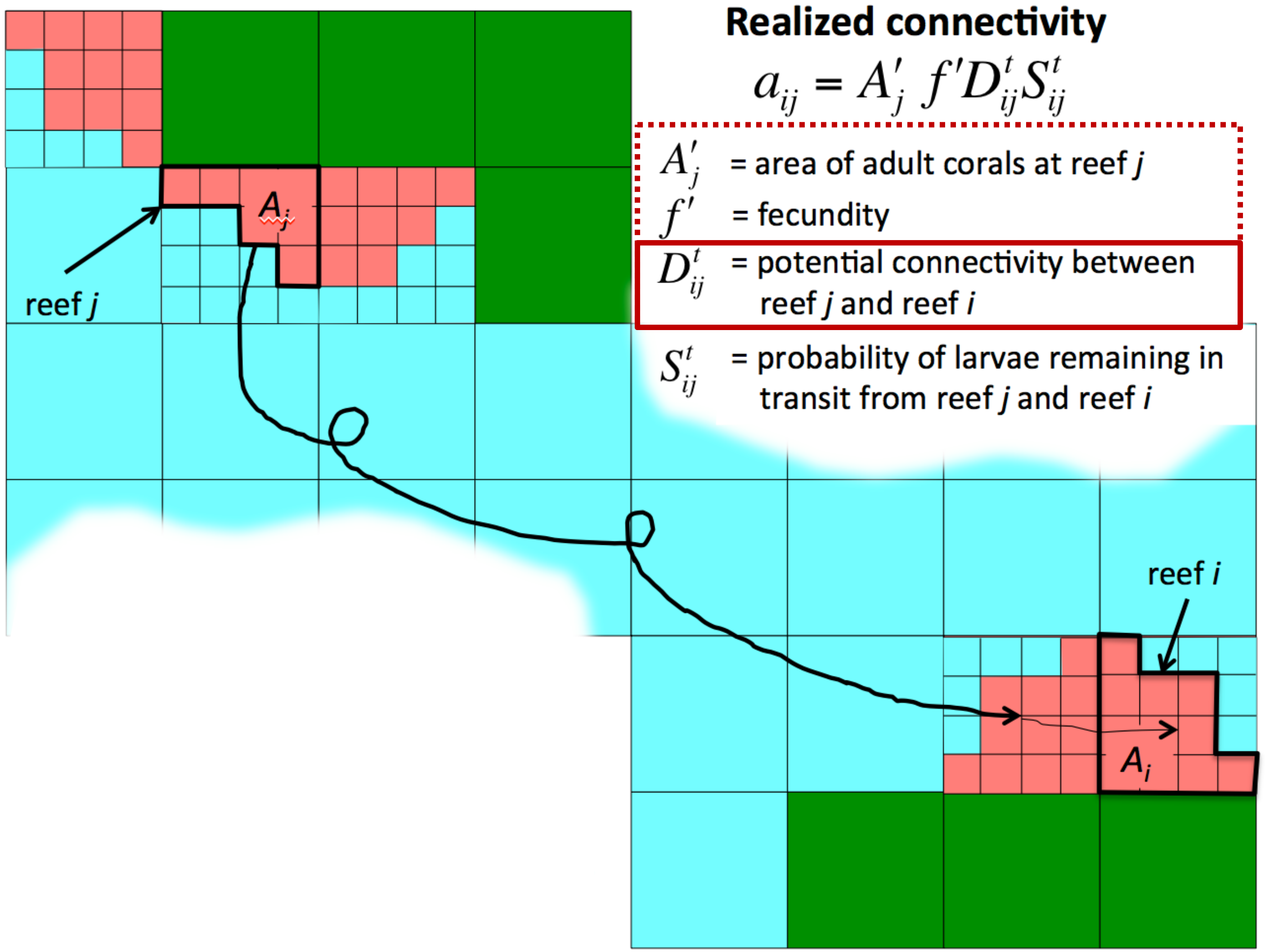
Reef recovery through re-seeding

Coral spawning

Larval dispersal

CT-ROMS: *Potential* Connectivity

Watson et al. 2012



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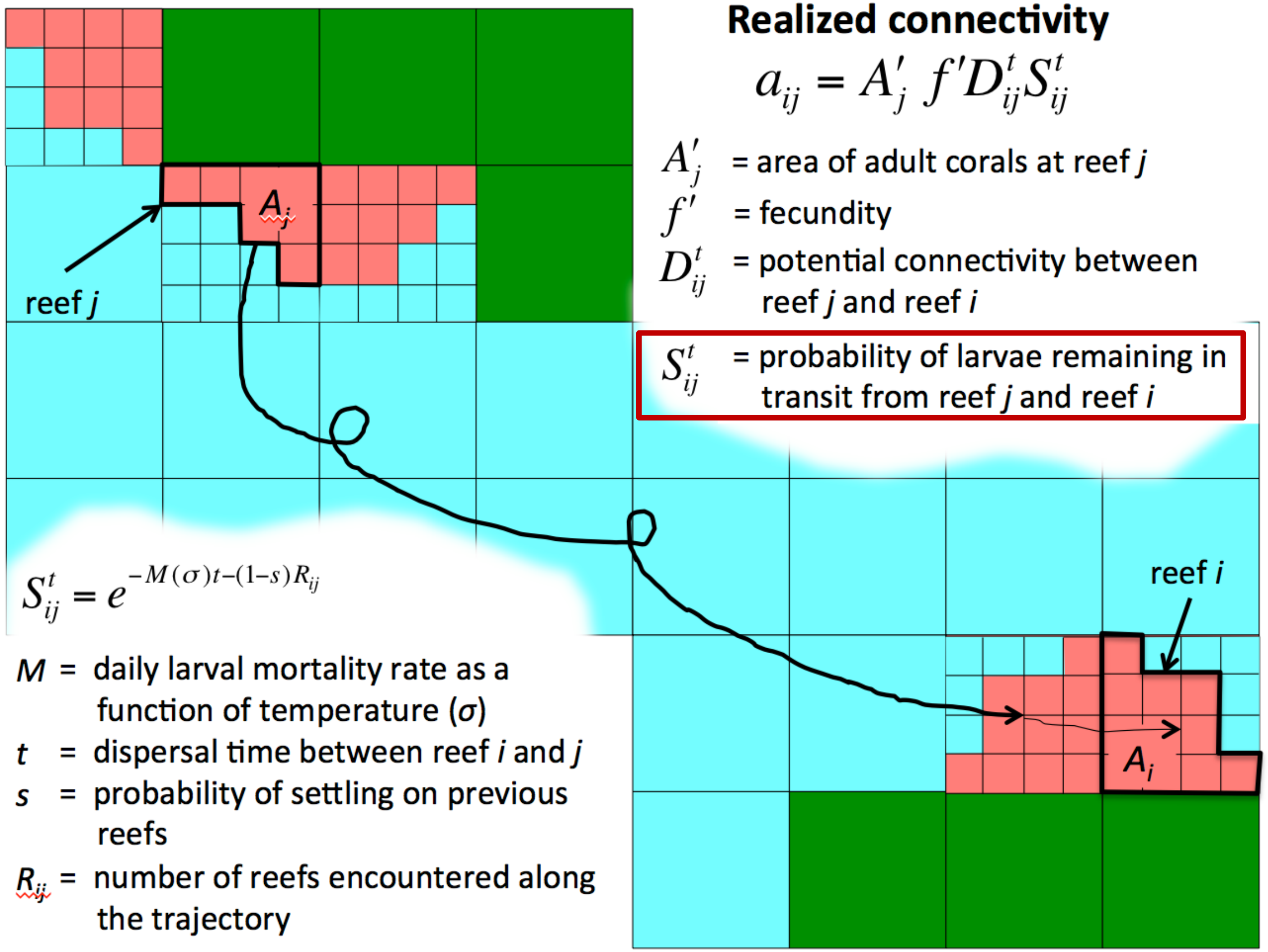


Realized connectivity

$$a_{ij} = A'_j \, f' D^t_{ij} S^t_{ij}$$

A'_j = area of adult corals at reef *j*

f' = fecundity

D^t_{ij} = potential connectivity between reef *j* and reef *i*

S^t_{ij} = probability of larvae remaining in transit from reef *j* and reef *i*

$$S^t_{ij} = e^{-M(\sigma)t-(1-s)R_{ij}}$$

M = daily larval mortality rate as a function of temperature (σ)

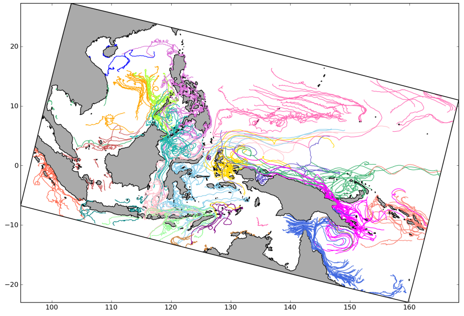
t = dispersal time between reef *i* and *j*

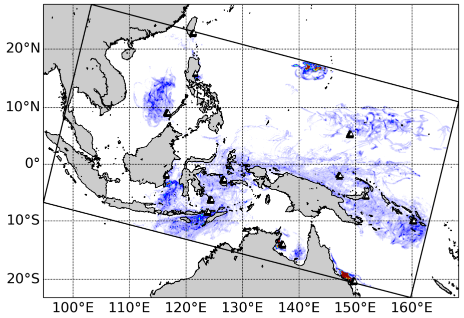
s = probability of settling on previous reefs

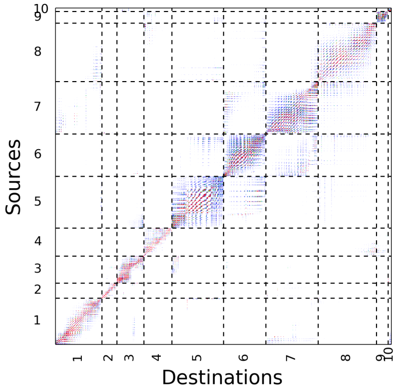
R_{ij} = number of reefs encountered along the trajectory

Connectivity in the Coral Triangle

Methods







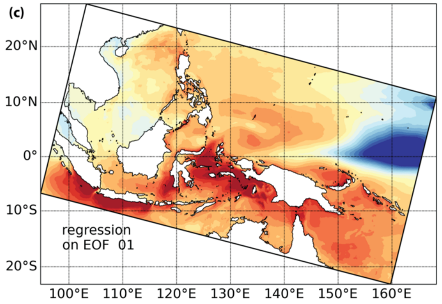
Particle release

TRACMASS

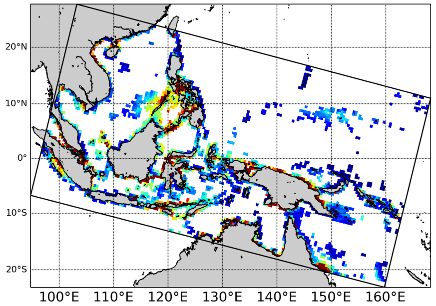
CT-ROMS velocity fields

→ Lagrangian trajectories → Lagrangian PDFs → Potential connectivity →

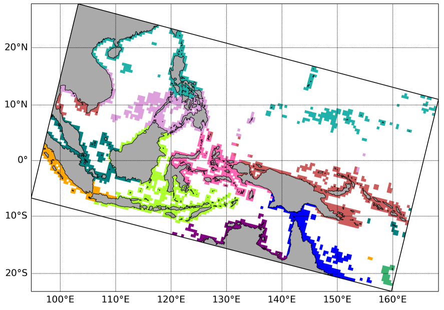
Spatio-temporal patterns



Larval sources/sinks



Subpopulations



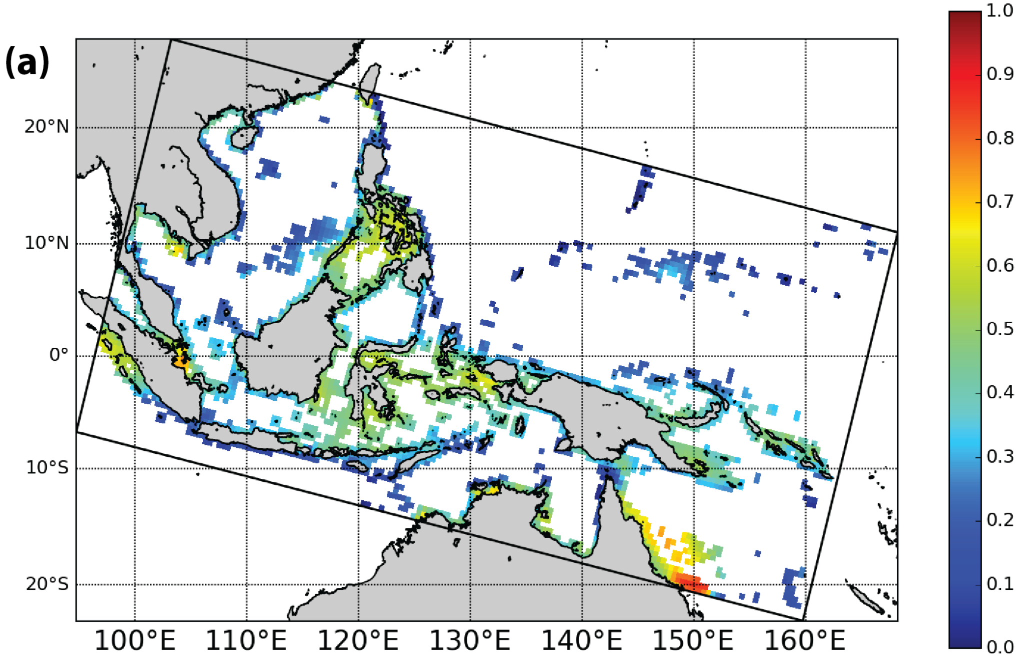
- *Simulated larval release of a broadcast spawner*
- *2500 reef sites*
- *8000 particles released per site*
- *47 years of larval releases for both fall and spring*

Thompson et al. in prep, *Prog. Oceanog.*

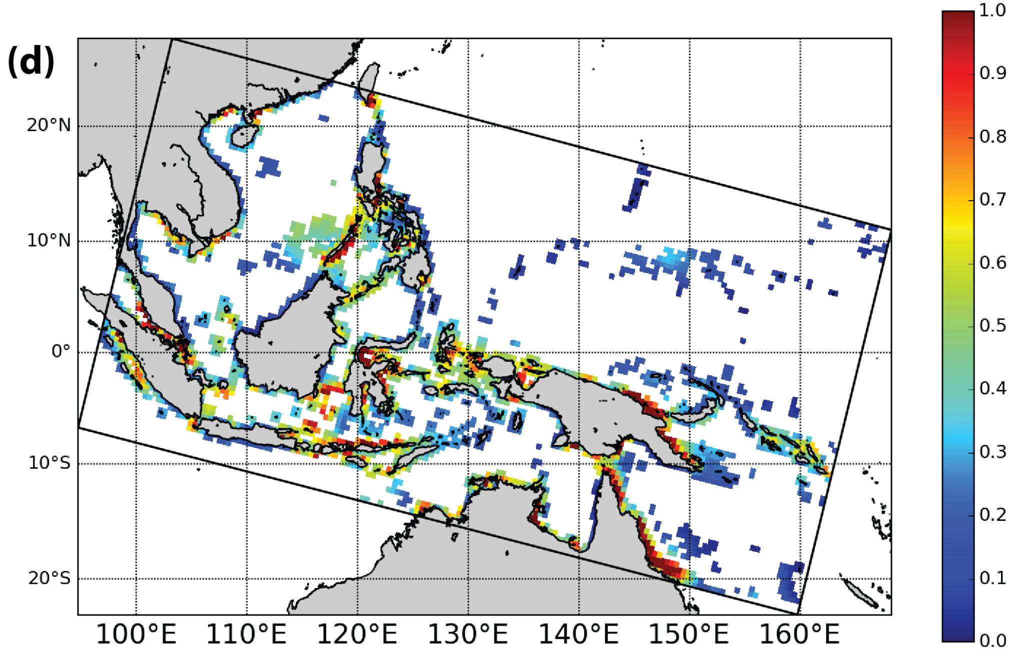
Connectivity in the Coral Triangle

Results: Important source and sink regions

Source power



Sink power

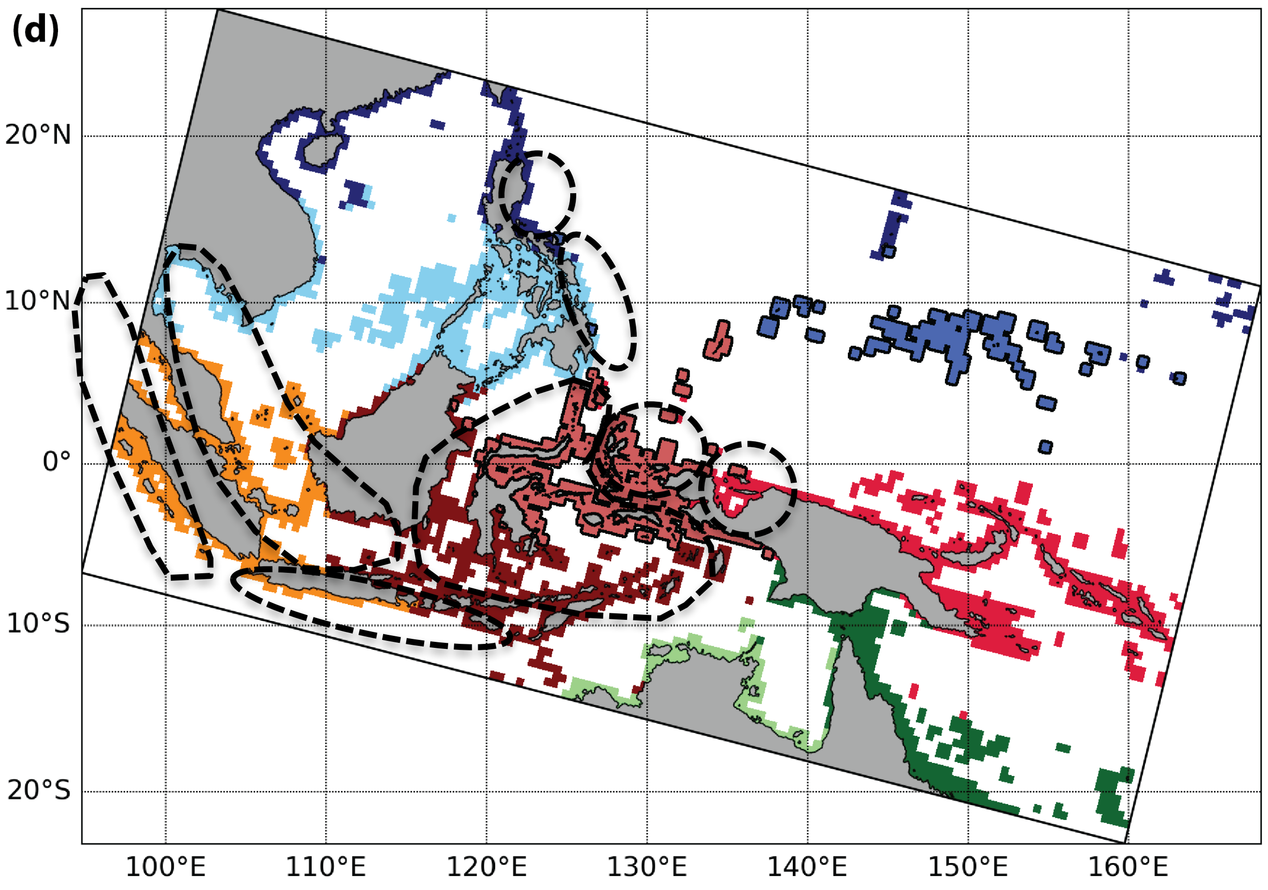


Thompson et al. in prep.

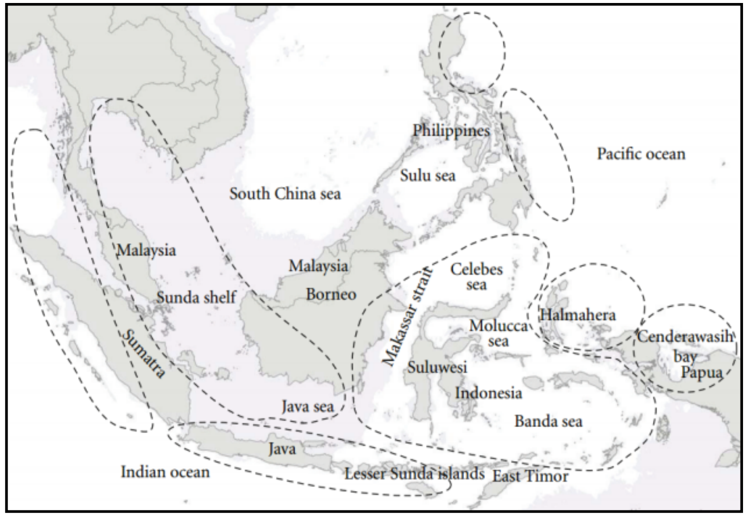
Connectivity in the Coral Triangle

Results: Subpopulations

PC-based subpopulations of a broadcasting coral



Genetics-based subpopulations of multiple invertebrate species

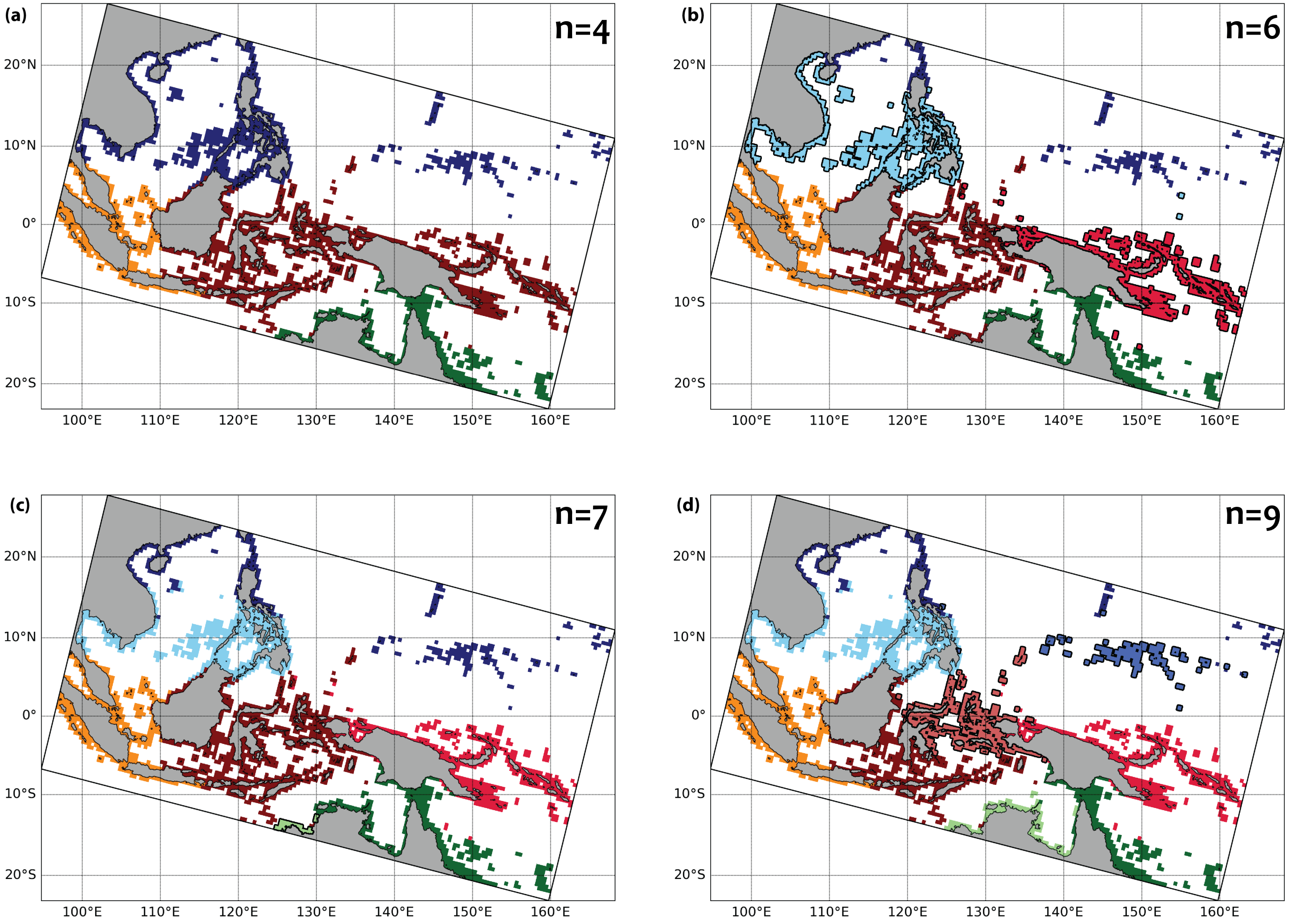


Carpenter *et al.* 2011

Thompson et al. in prep.

Connectivity in the Coral Triangle

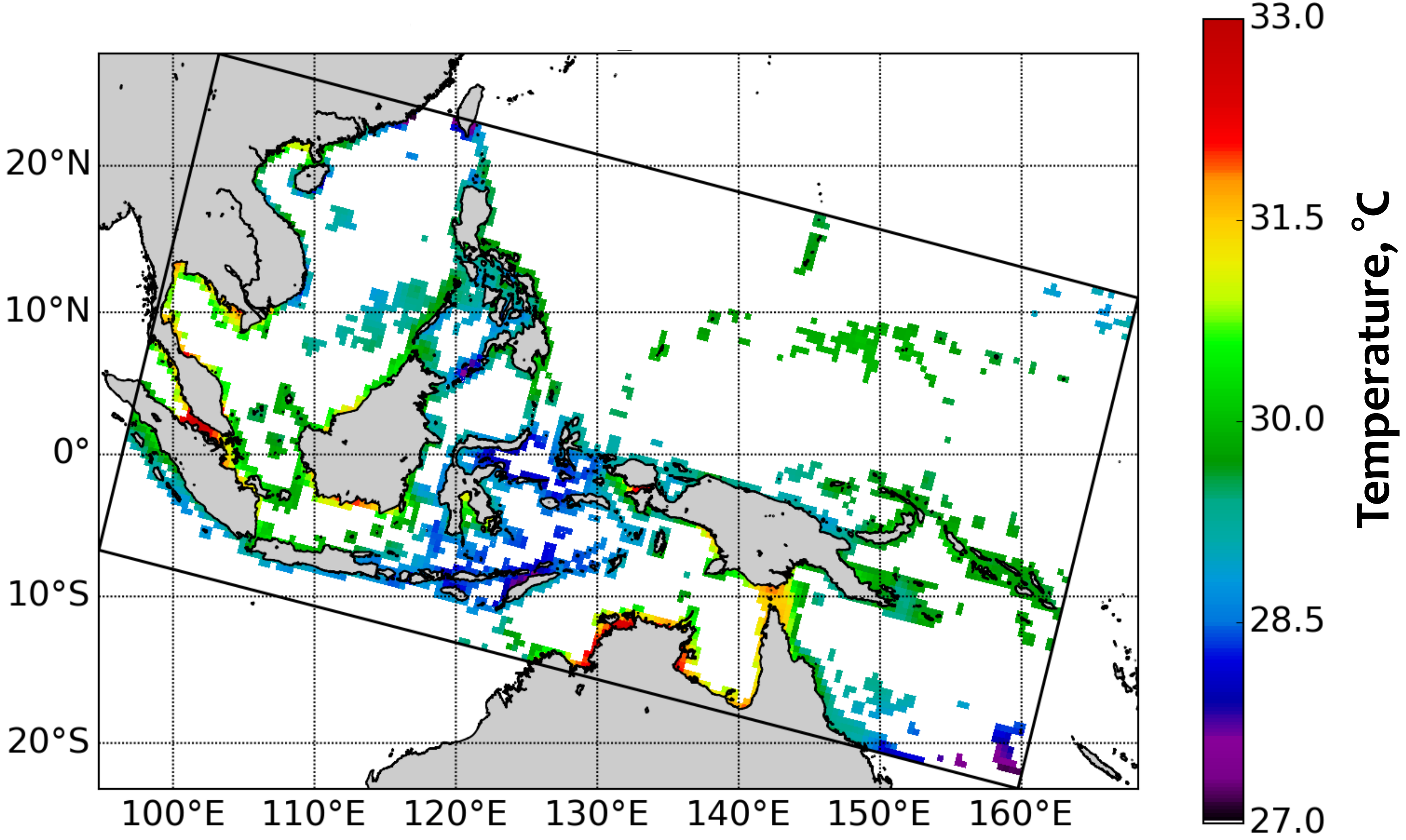
Results: Subpopulations



Thompson et al. in prep.

Thermal Stress Threshold

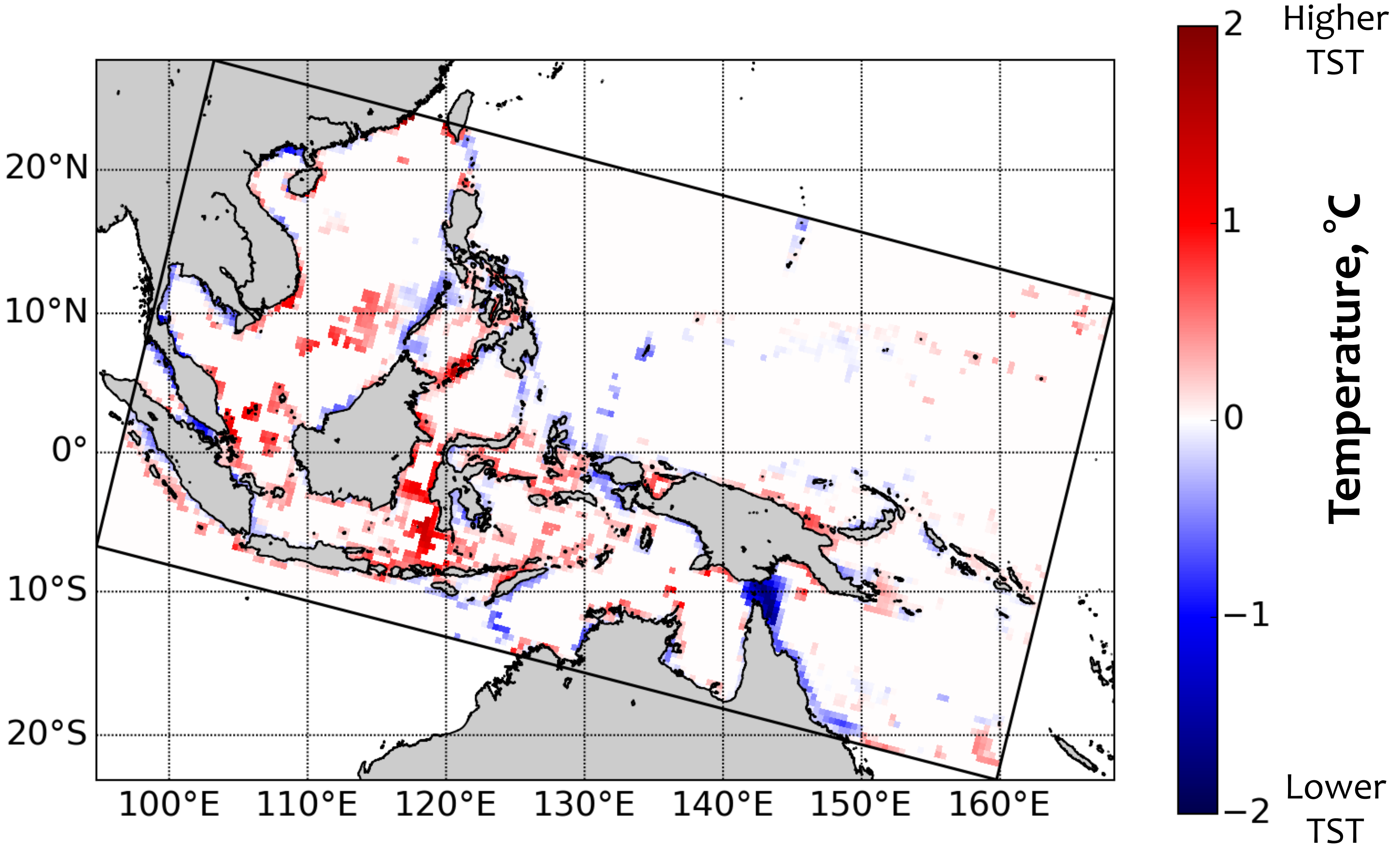
Based on local temperature



Kleypas et al. 2016 *GCB*

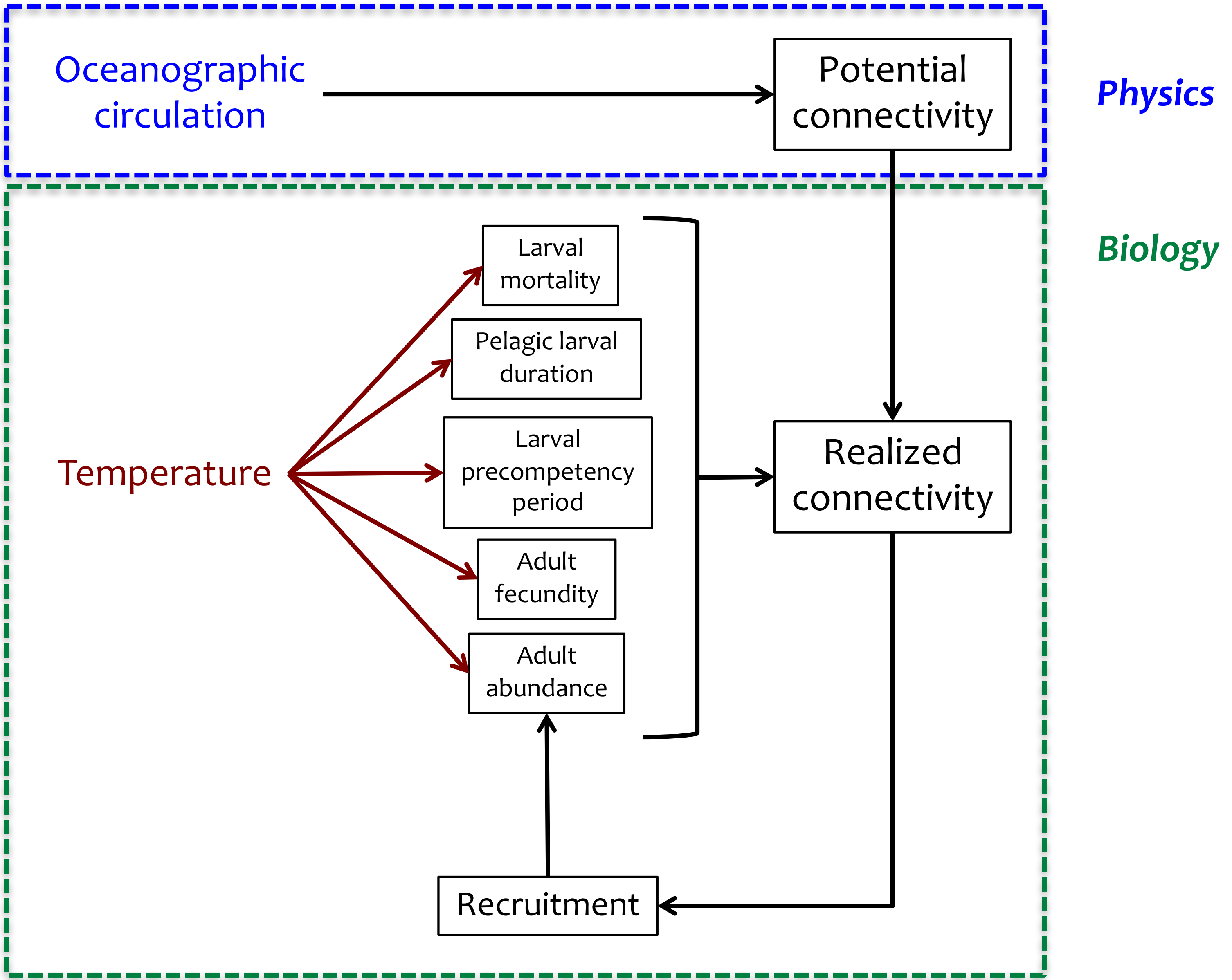
Larval transport across temperature gradients

CHANGE in thermal stress threshold due to Potential Connectivity, 30-days



Kleypas et al. 2016 *GCB*

Realized Connectivity



Knowledge Gained

Physics:

- For reefs in the Coral Triangle, we need to understand a wide range of scales – from internal tides to inter-ocean exchange
- The ocean is 3D and turbulent!
- In this region there is significant heterogeneity

Biology:

- Warming over the last 50 years has varied with region and depth
- Future warming is likely to be severe in most regions
- The environmental heterogeneity of the CT (temperature and connectivity) shows promise that some refugia may persist into the future

NCAR

Future Work

Multiply nested domains down to the reef scale

Ocean acidification and productivity

Extending these capabilities to other reef regions where data are available (e.g., US Pacific Is.)

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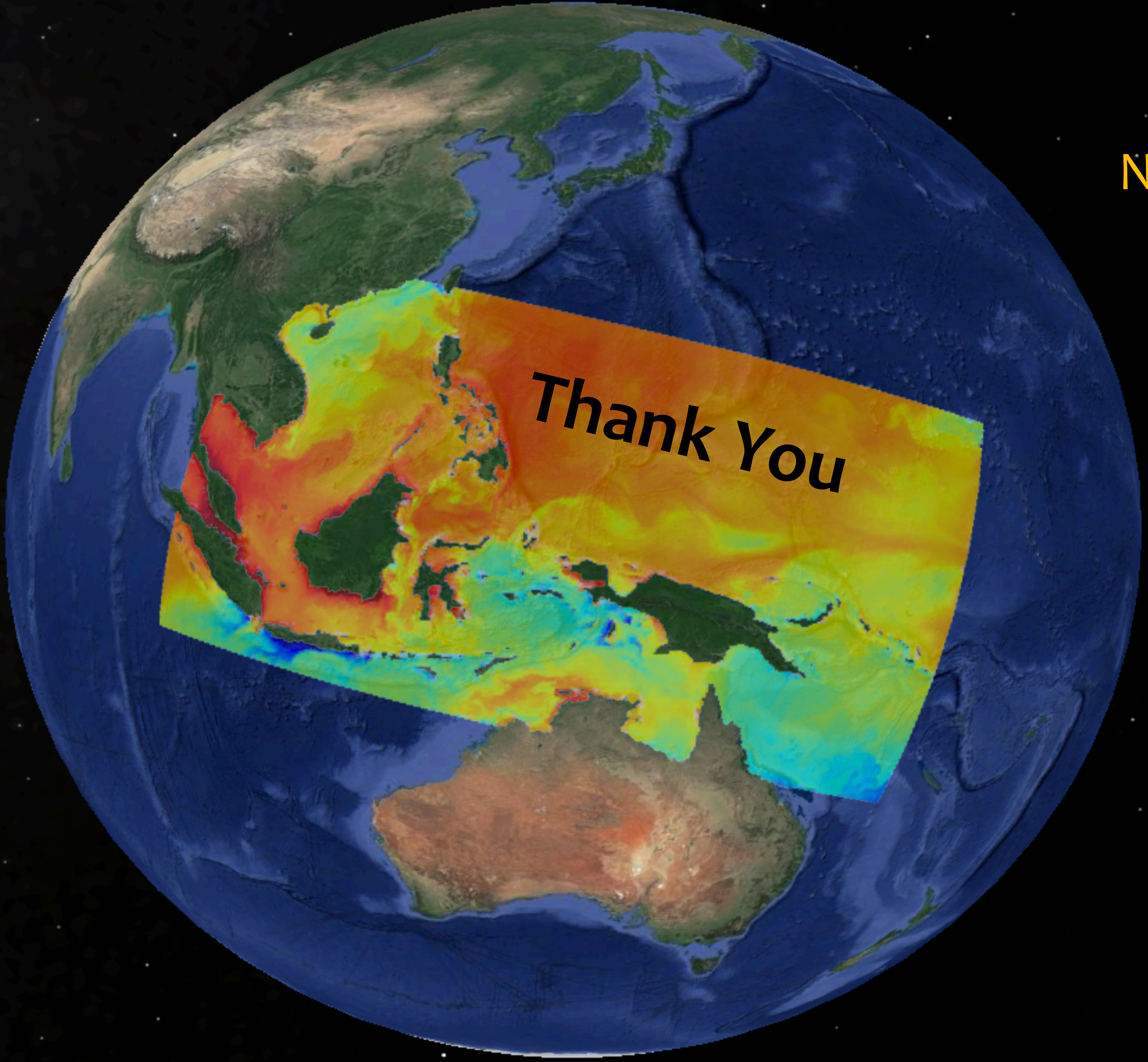

http://www.ctroms.ucar.edu/