

Marine
Heatwaves
in the Context
of Compound
Extremes

ICTP-CLIVAR Summer School 24-
24-29/07/2023

Regina R. Rodrigues
UFSC, Brazil



Compound Events

Motivation



Compound events **impact** human and natural systems



They are a combination of **multiple hazards** and/or drivers



Understanding the **physical processes** of compounding



Improving **predictability**, detection, attribution



Assessing societal and environmental impacts and **risks**



There are different **types** of compound events



Compound Events

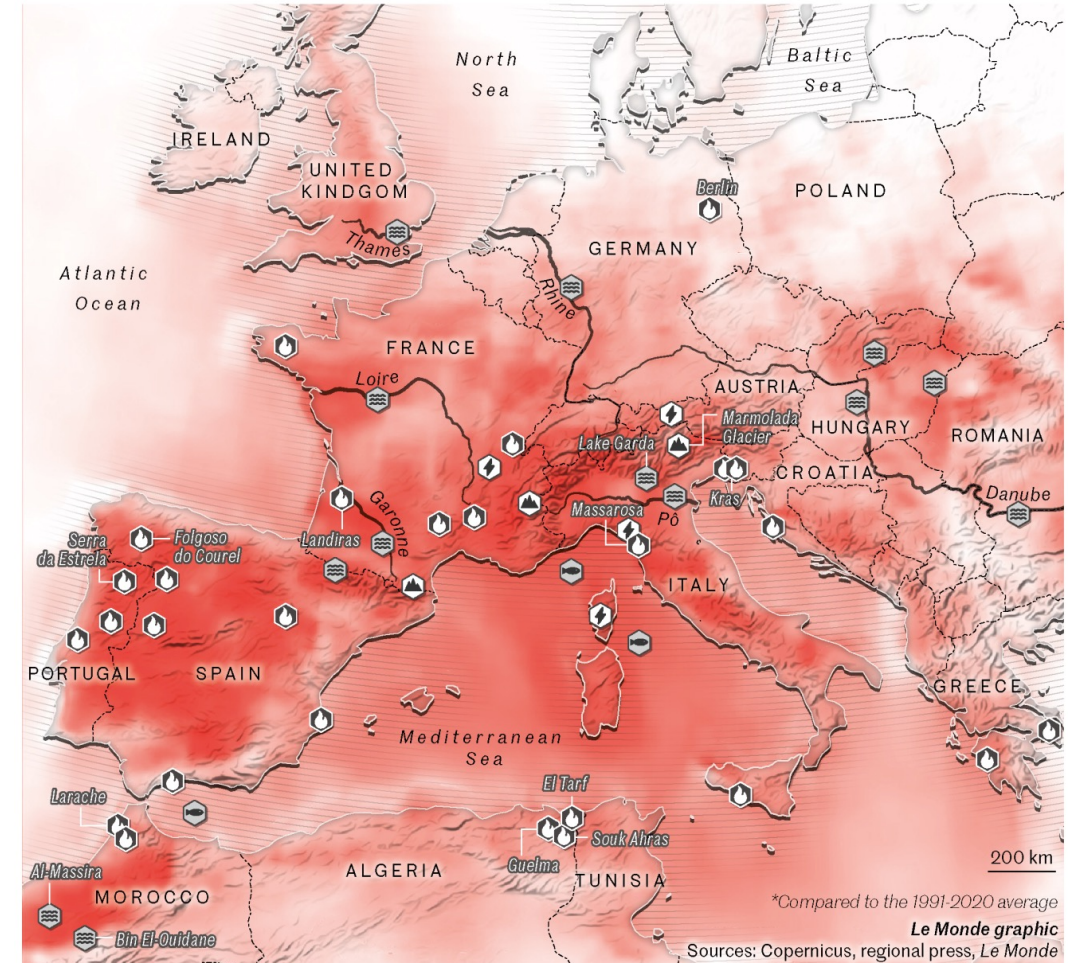
Motivation

- ✓ Simultaneous multiple hazards (Zscheischler et al. 2020)

2022: An abnormally hot summer with extreme weather events

Temperature anomalies in July 2022*
Legend: < 0°C (light red), > +5°C (dark red)

- 🔥 Major fires
- 🌊 Main dried-up rivers, lakes, and other water bodies
- ⚡ Violent rains and storms
- 🏔️ Rockslides in mountains and glacier collapses
- 🌊 Marine heatwaves

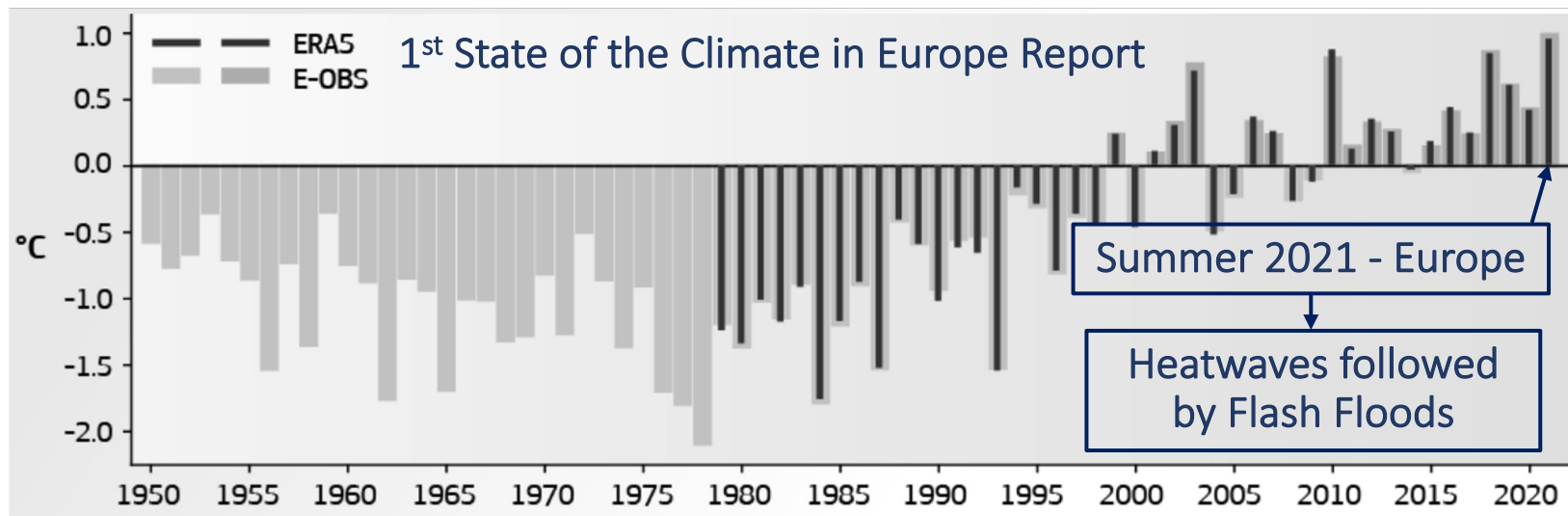




Compound Events

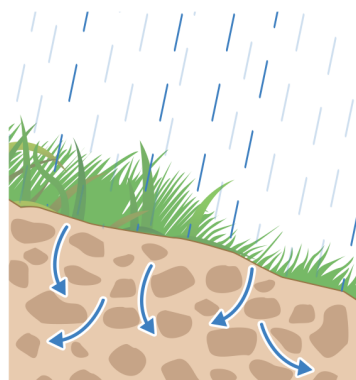
Motivation

- ✓ Successive events (Zscheischler et al. 2020)



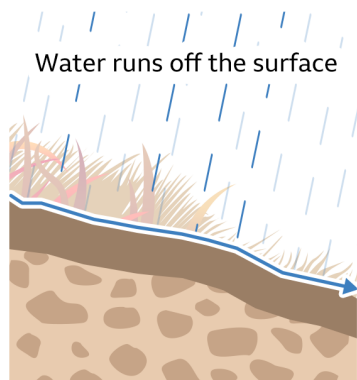
Why flash floods happen after drought

Normal conditions



Soil absorbs water like a sponge

Drought conditions



Hard layer of soil repels water

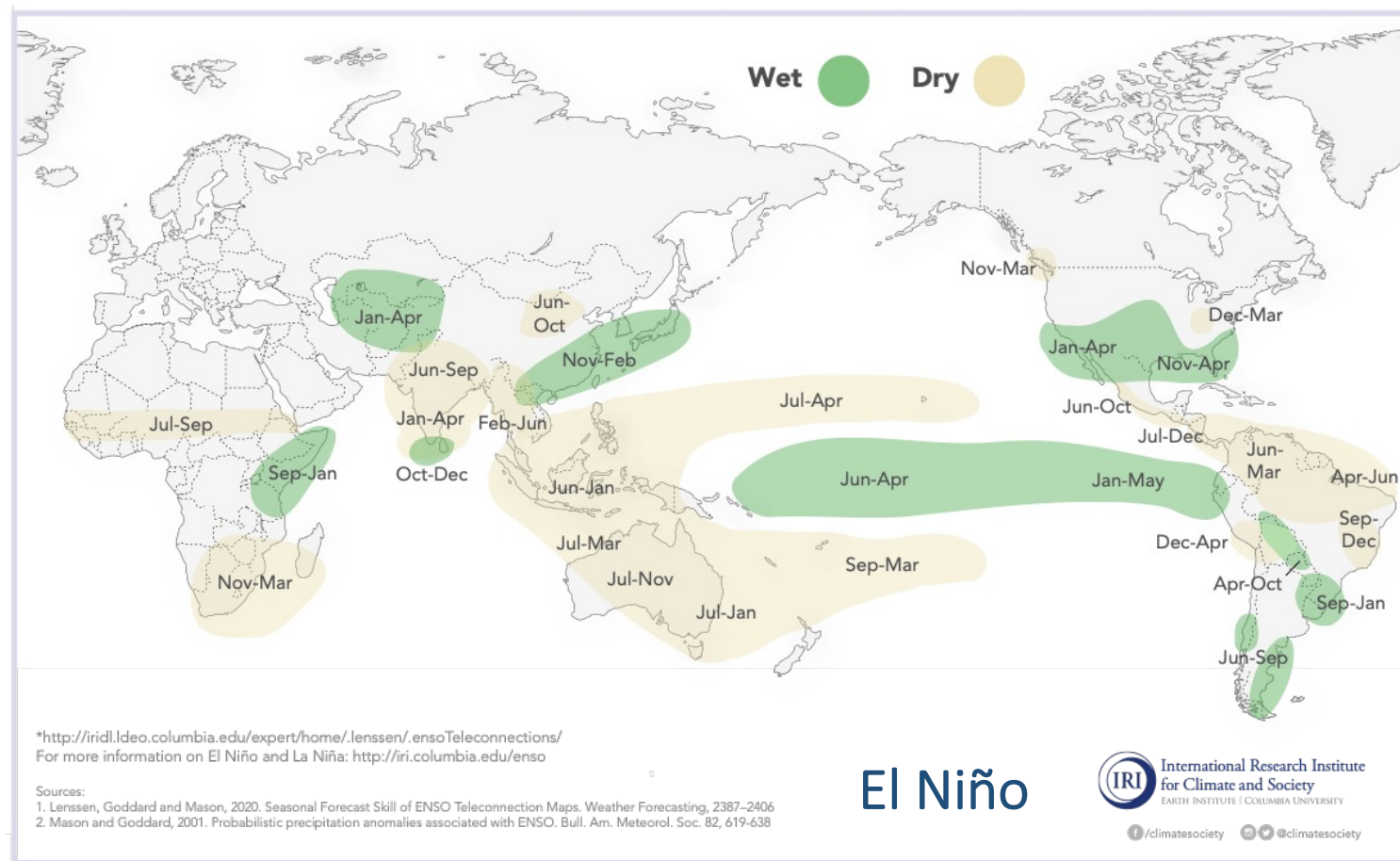
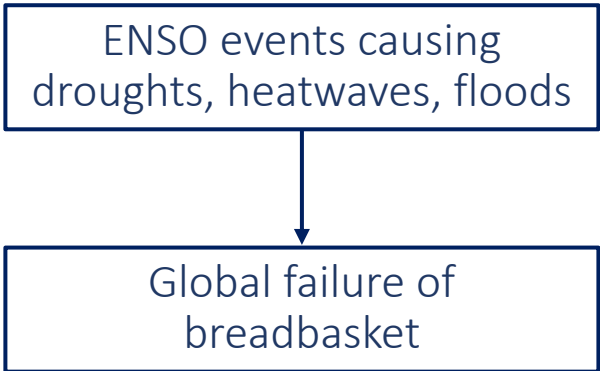




Compound Events

Motivation

- ✓ Spatially concurrent hazards - ENSO (Zscheischler et al. 2020)





Compound Events

Motivation

(Gruber et al. 2021; Burger et al. 2022)



Marine heatwaves are periods of extreme **ocean** temperatures



Marine heatwaves have different physical **drivers**



Marine heatwaves can cause devastating **impacts** on marine life



In many cases, marine heatwaves **co-occur** with other extremes



Extreme events on **land**, droughts, heatwaves, etc.



Extreme events in the **ocean**, of high acidity, low oxygen, etc.



Compound Events

Motivation

Land

Substantial

Land-Ocean

Limited

Ocean

Growing

nature reviews earth & environment

A typology of compound weather and climate events

[Jakob Zscheischler](#) ✉, [Olivia Martius](#), [Seth Westra](#), [Emanuele Bevacqua](#), [Colin Raymond](#), [Radley M. Horton](#), [Bart van den Hurk](#), [Amir AghaKouchak](#), [Aglaé Jézéquel](#), [Miguel D. Mahecha](#), [Douglas Maraun](#),

nature geoscience

Common cause for severe droughts in South America and marine heatwaves in the South Atlantic

[Regina R. Rodrigues](#) ✉, [Andréa S. Taschetto](#), [Alex Sen Gupta](#) & [Gregory R. Foltz](#)

nature

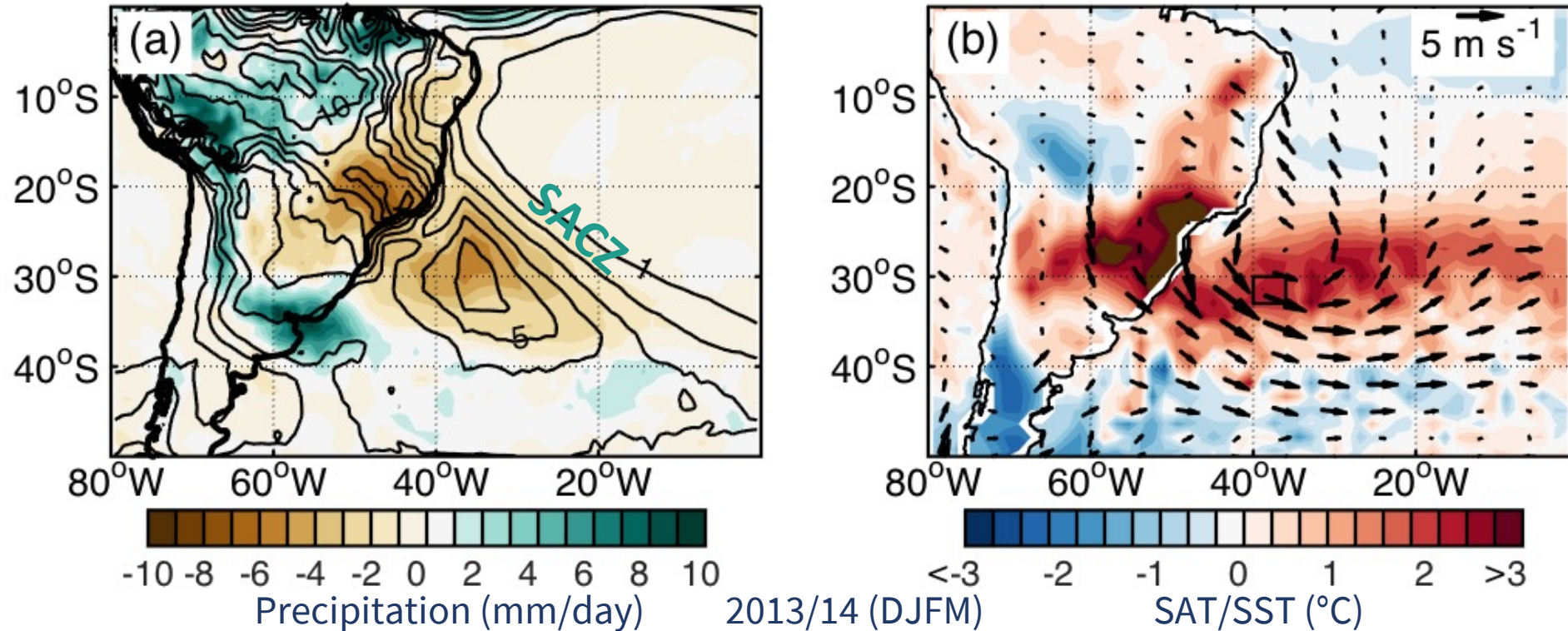
Biogeochemical extremes and compound events in the ocean

[Nicolas Gruber](#) ✉, [Philip W. Boyd](#), [Thomas L. Frölicher](#) & [Meike Vogt](#)



Compound Events

Land-Ocean Compound



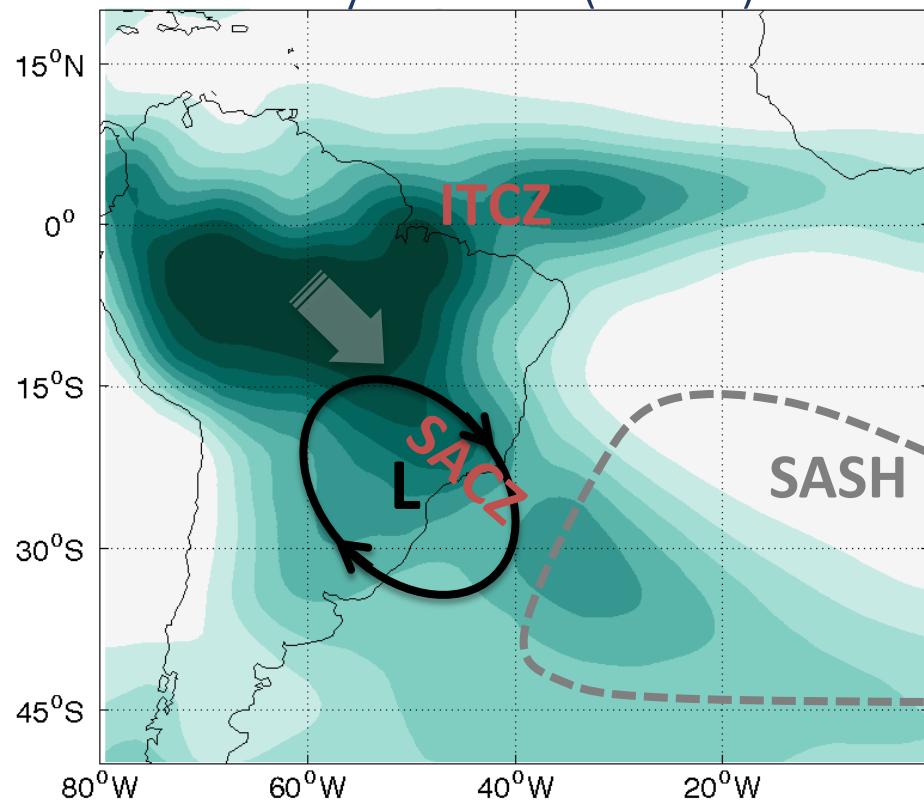
✓ Marine heatwaves are associated with droughts and land heatwaves → Compound extreme events



Compound Events

Land-Ocean Compound

Rainy Season (DJFM)



Precipitation (mm/day)

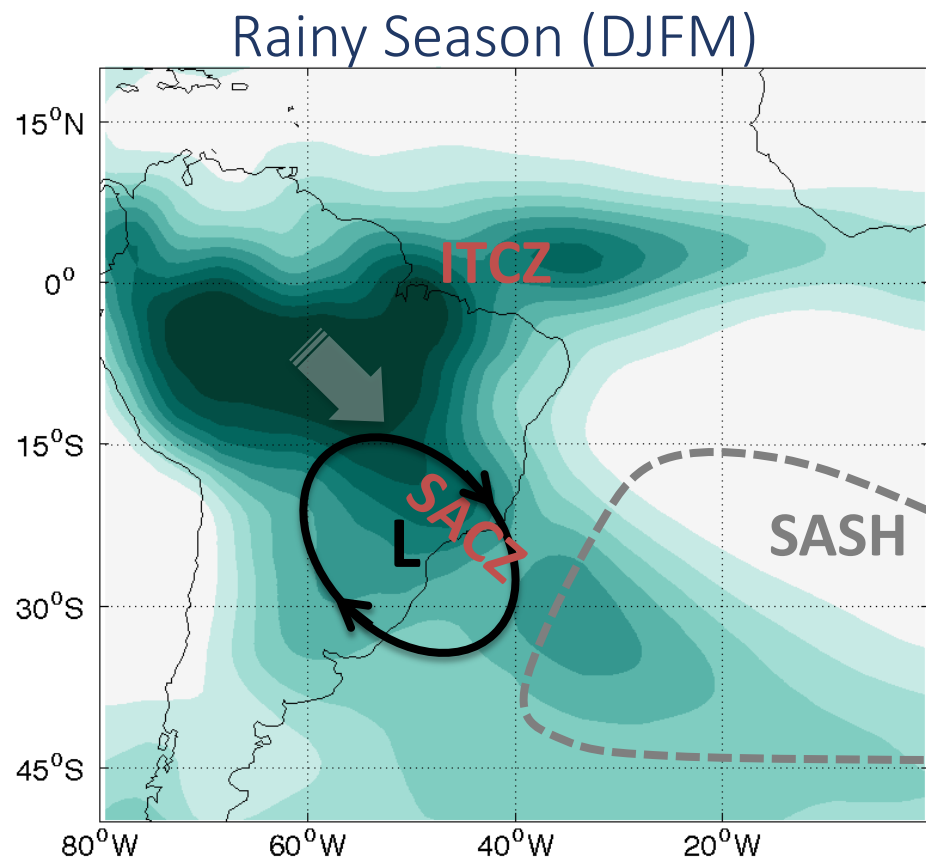
2013/14 (DJFM)

SAT/SST (°C)



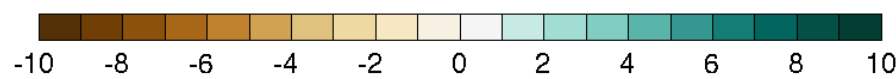
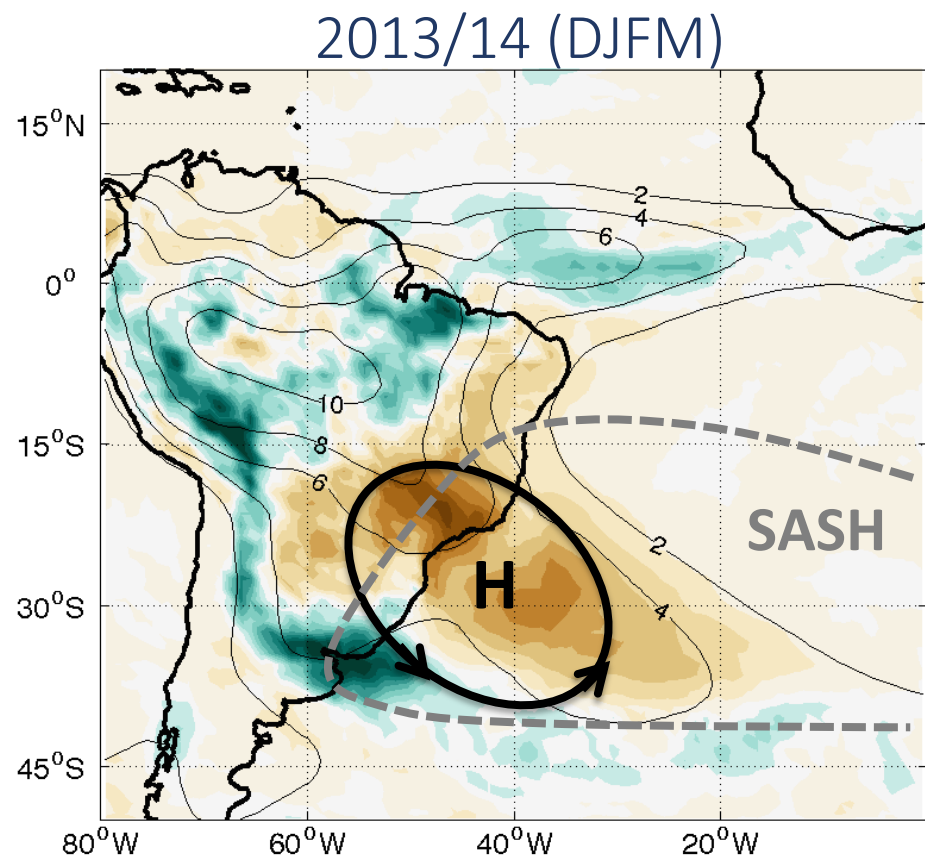
Compound Events

Land-Ocean Compound



Climatology

Precipitation (mm/day)



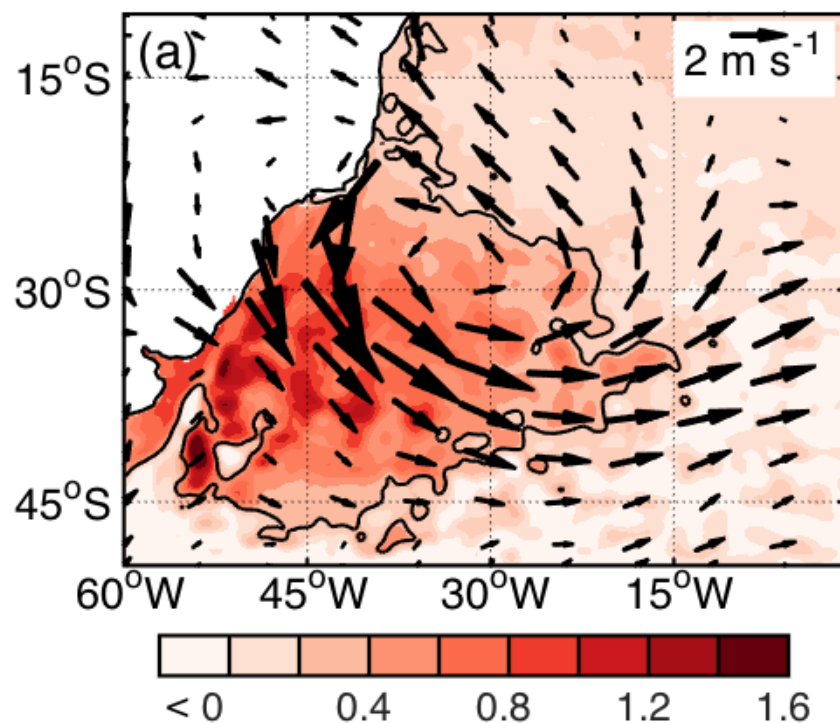
Anomalies



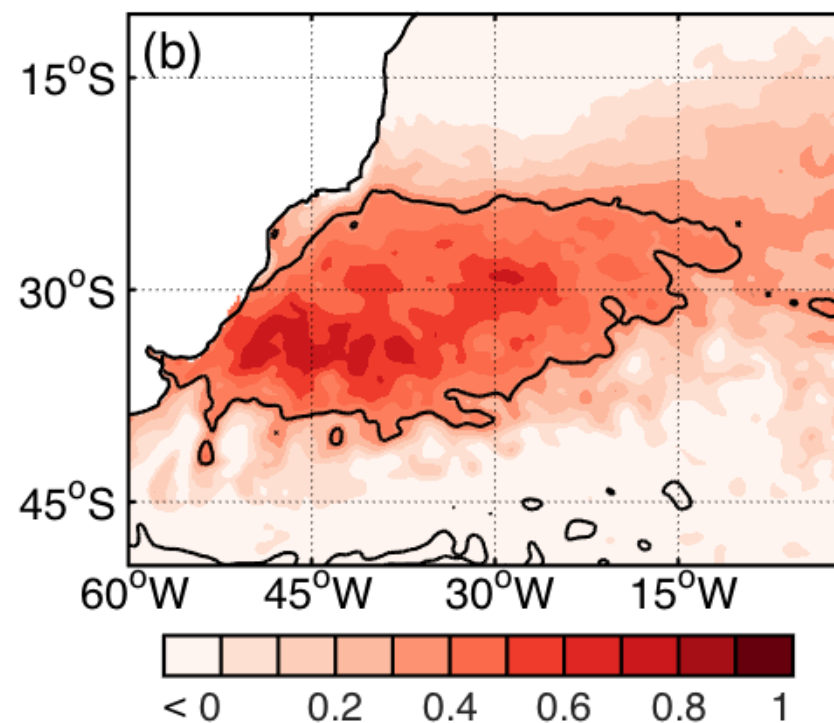
Compound Events

Land-Ocean Compound

Composites SST+WIND all MHWs



Correlation SST - Blocking

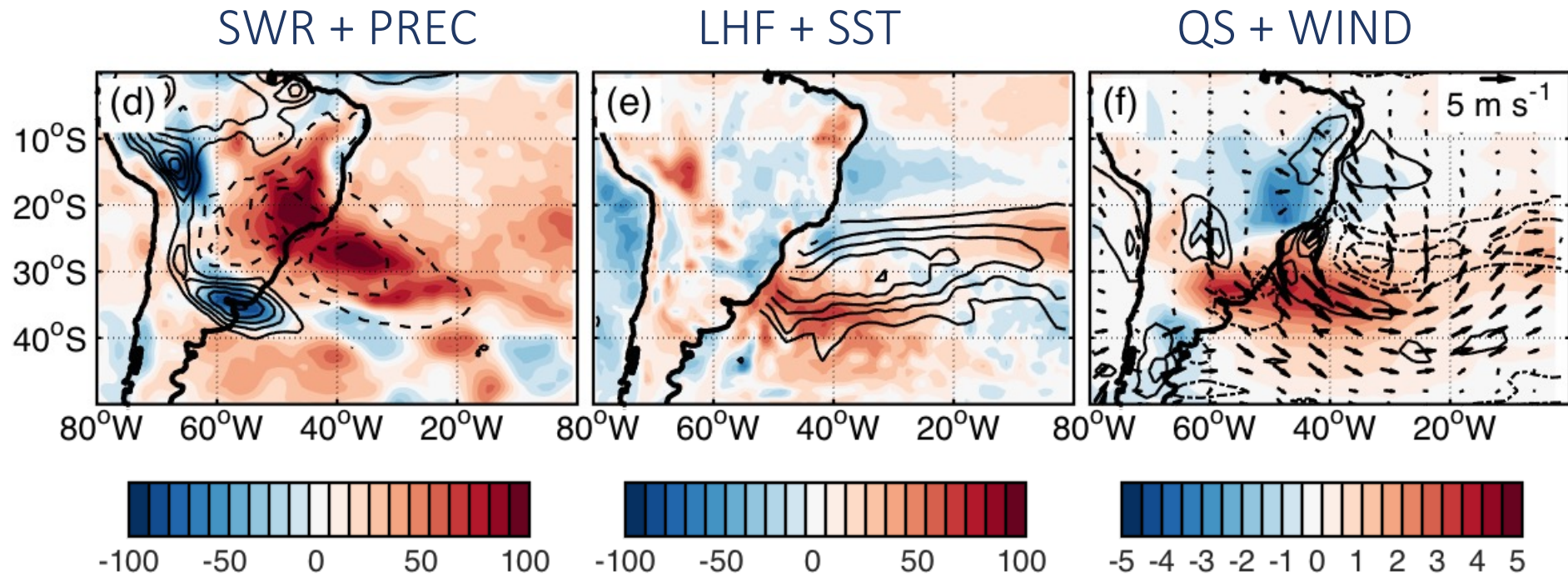


✓ Up to 60% of MHW days occur simultaneously with atmospheric blocking days (1982-2016)



Compound Events

Land-Ocean Compound

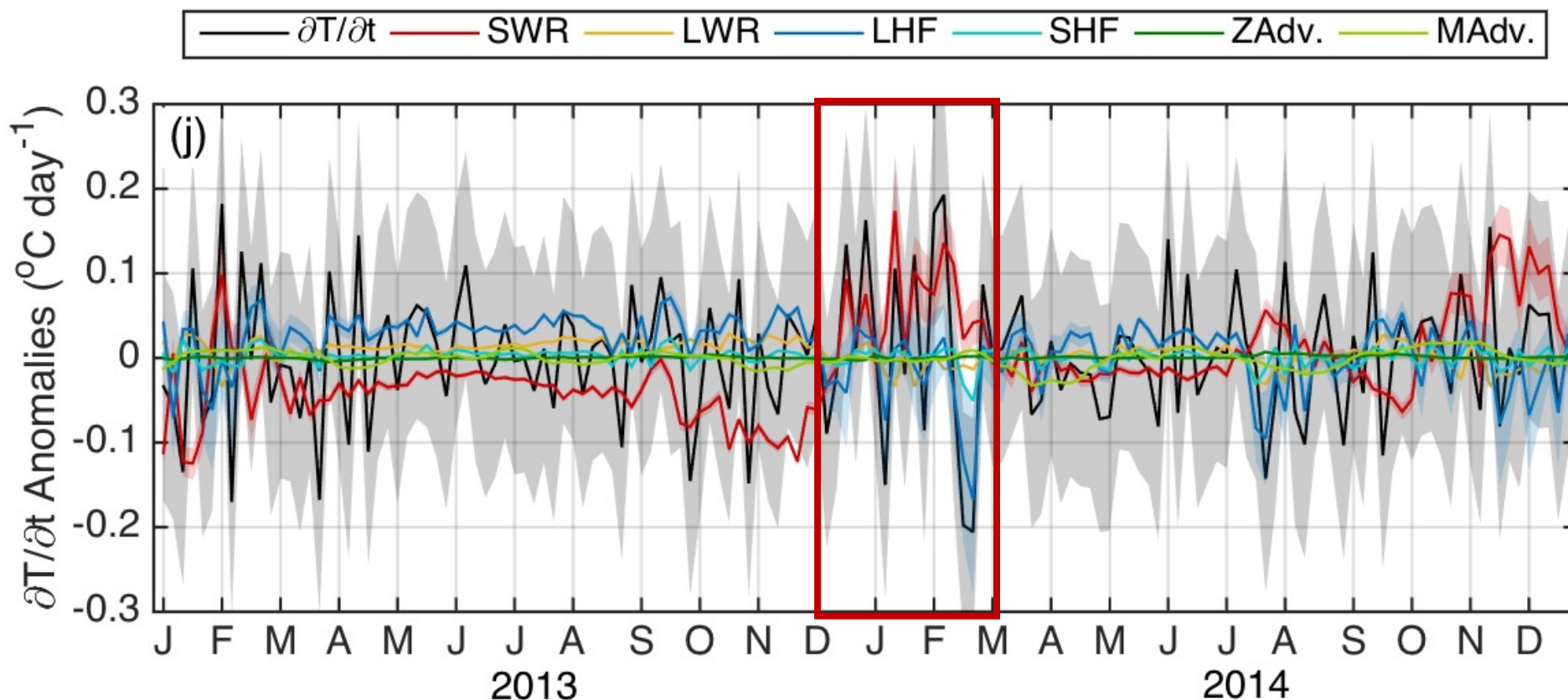


Surface heat fluxes during the 2013/14 Event



Compound Events

Land-Ocean Compound

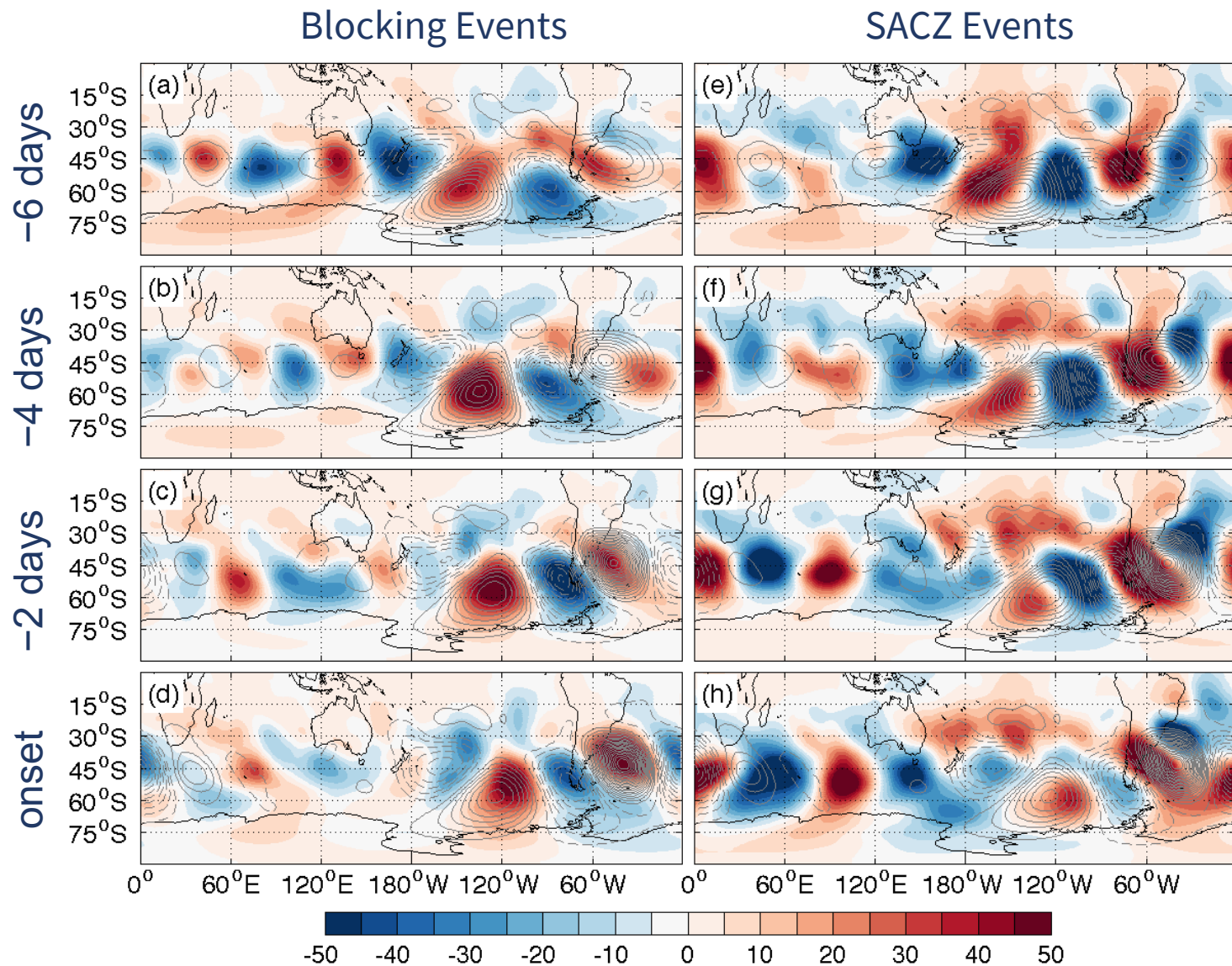


Mixed-Layer Temperature Budget ($30^{\circ}\text{S}-33^{\circ}\text{S}$, $36^{\circ}\text{W}-40^{\circ}\text{W}$)

$$\partial T/\partial t = -v \cdot \nabla T + Q_0/\rho C_p h + \epsilon$$



Compound Events

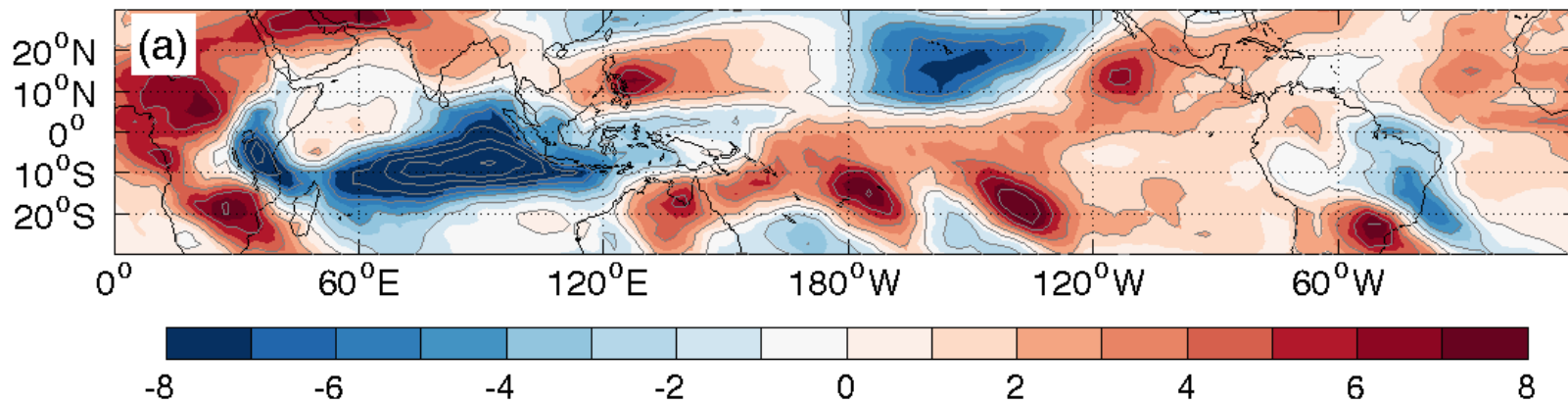


Composites of
Z200hPa for all
MHW (1979-2016)

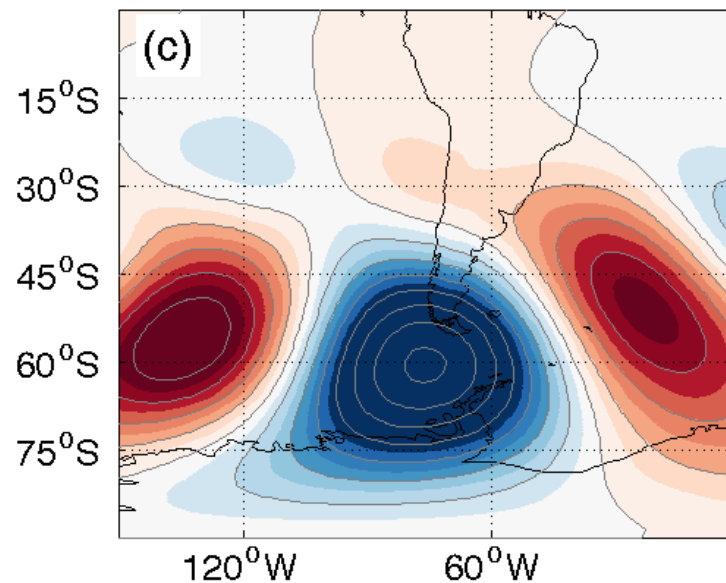
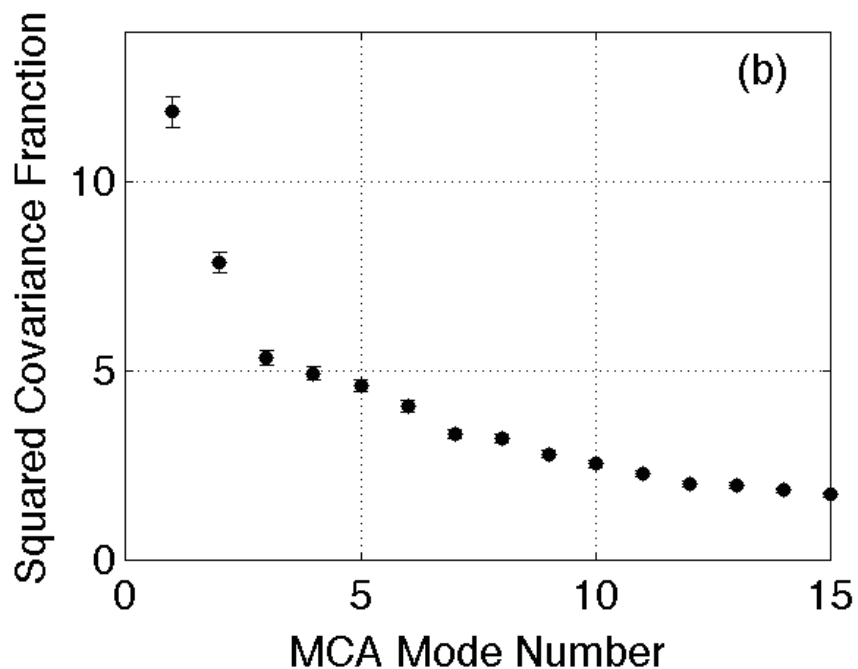
Rodrigues & Woollings (2017, JCLim)



Compound Events



MCA OLR-Z200hPa
(1979-2016)



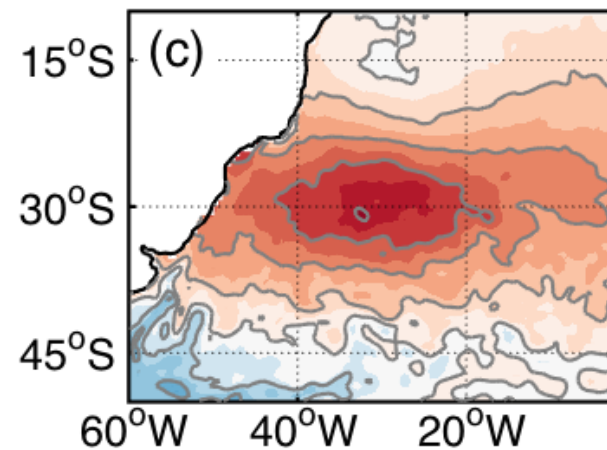
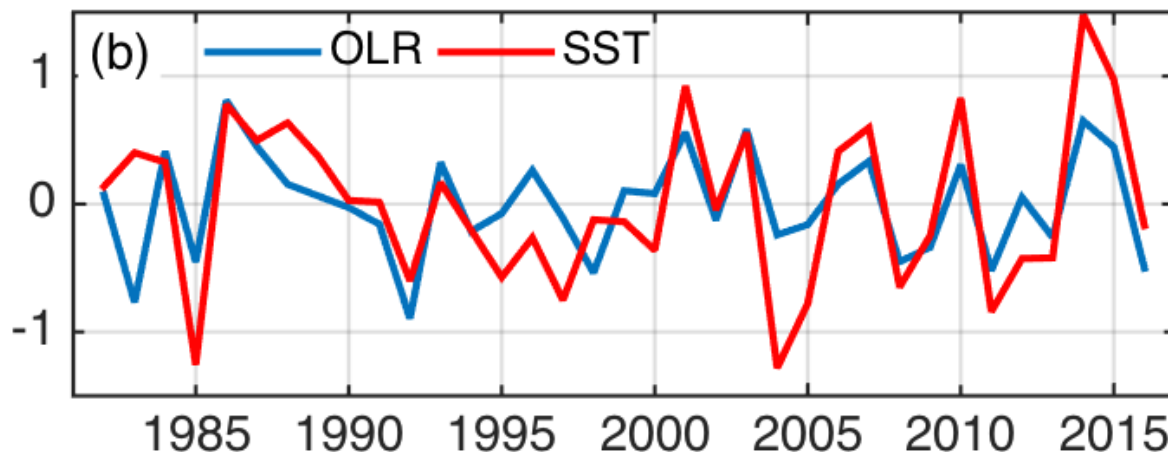
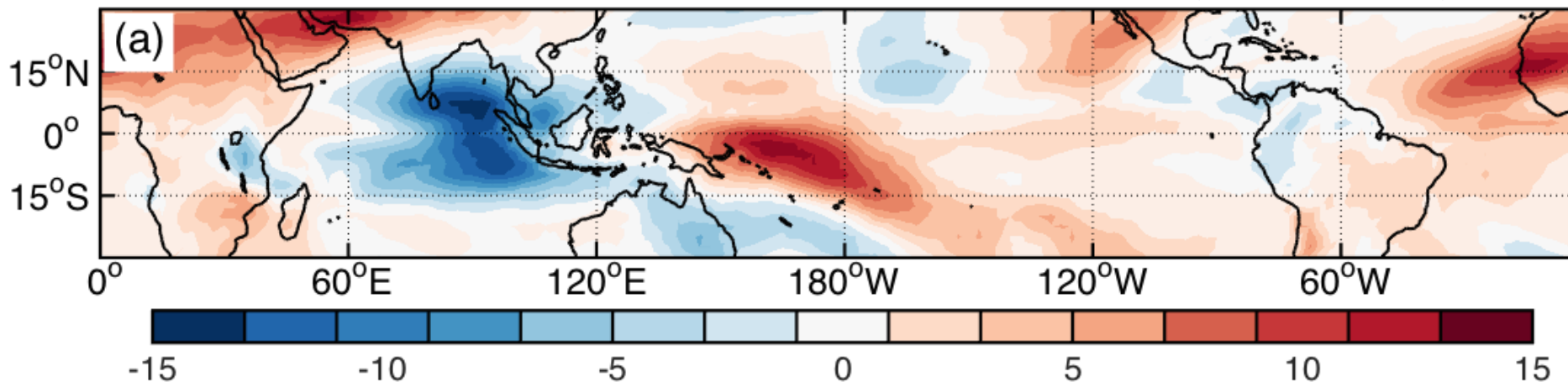
Rodrigues & Woollings (2017, JCLim)



Compound Events

Land-Ocean Compound

MCA OLR-SST (1982-2016)

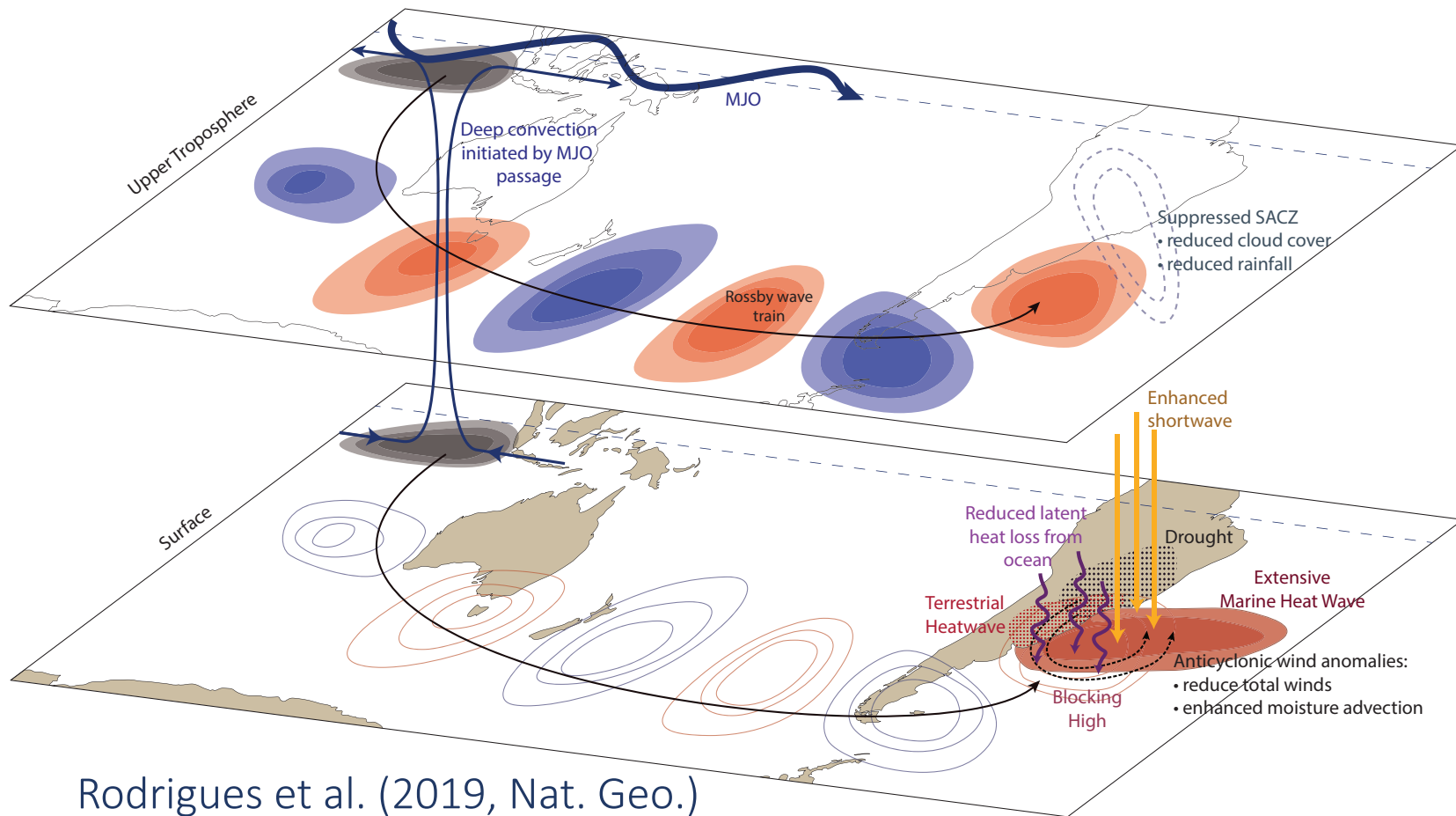


MJO Phases	1	2	3	4	5	6	7	8
MHW Frequency (%)	10	20	14	8	13	13	10	12



Compound Events

Land-Ocean Compound



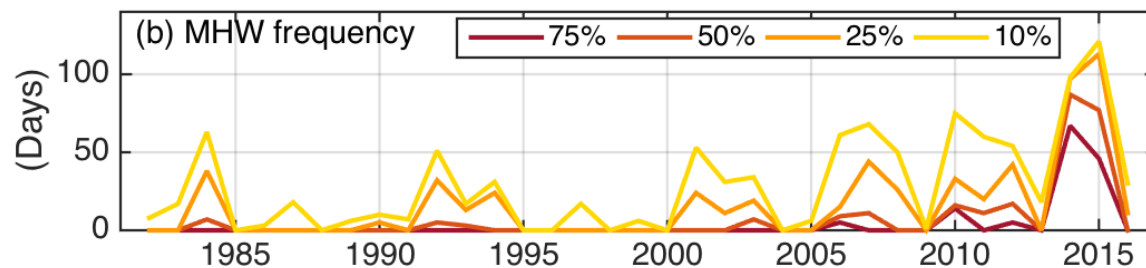
Rodrigues et al. (2019, Nat. Geo.)

- ✓ Droughts, marine and land heatwaves have the same cause
- ✓ Persistent high-pressure system (anticyclonic circulation)
- ✓ They can be remotely triggered (convection Indian Ocean – MJO)



Compound Events

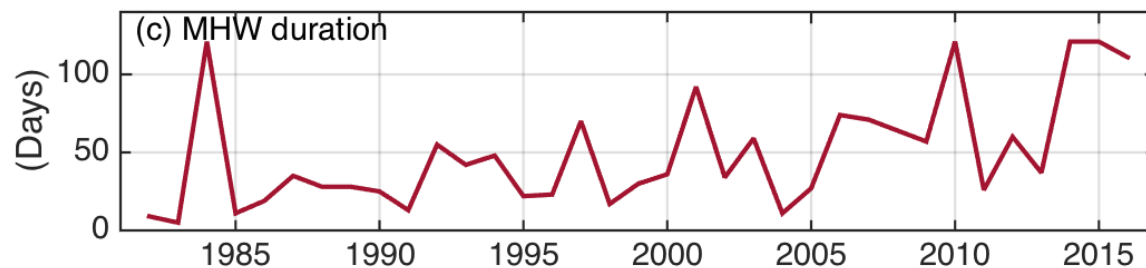
Frequency



✓ Trends per decade

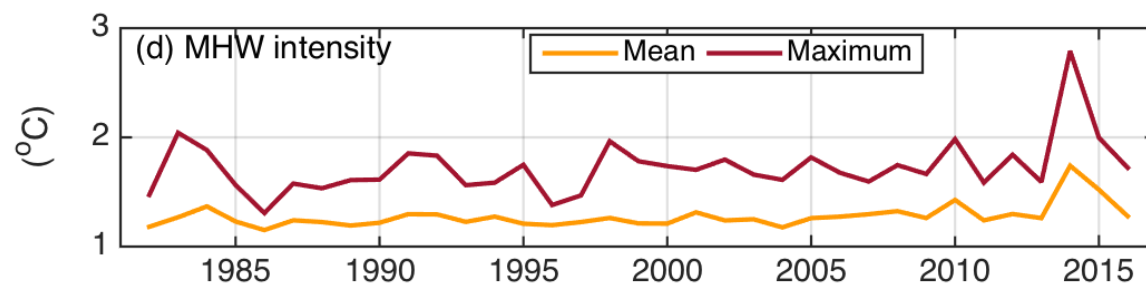
+8.4 days per year (50%)

Duration



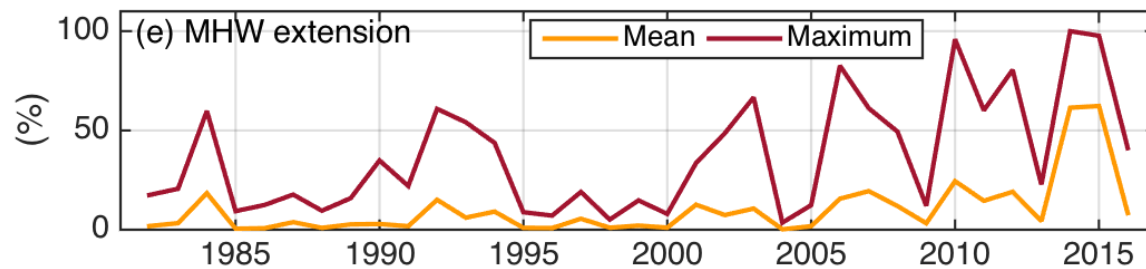
+18 days

Intensity



+0.05°C

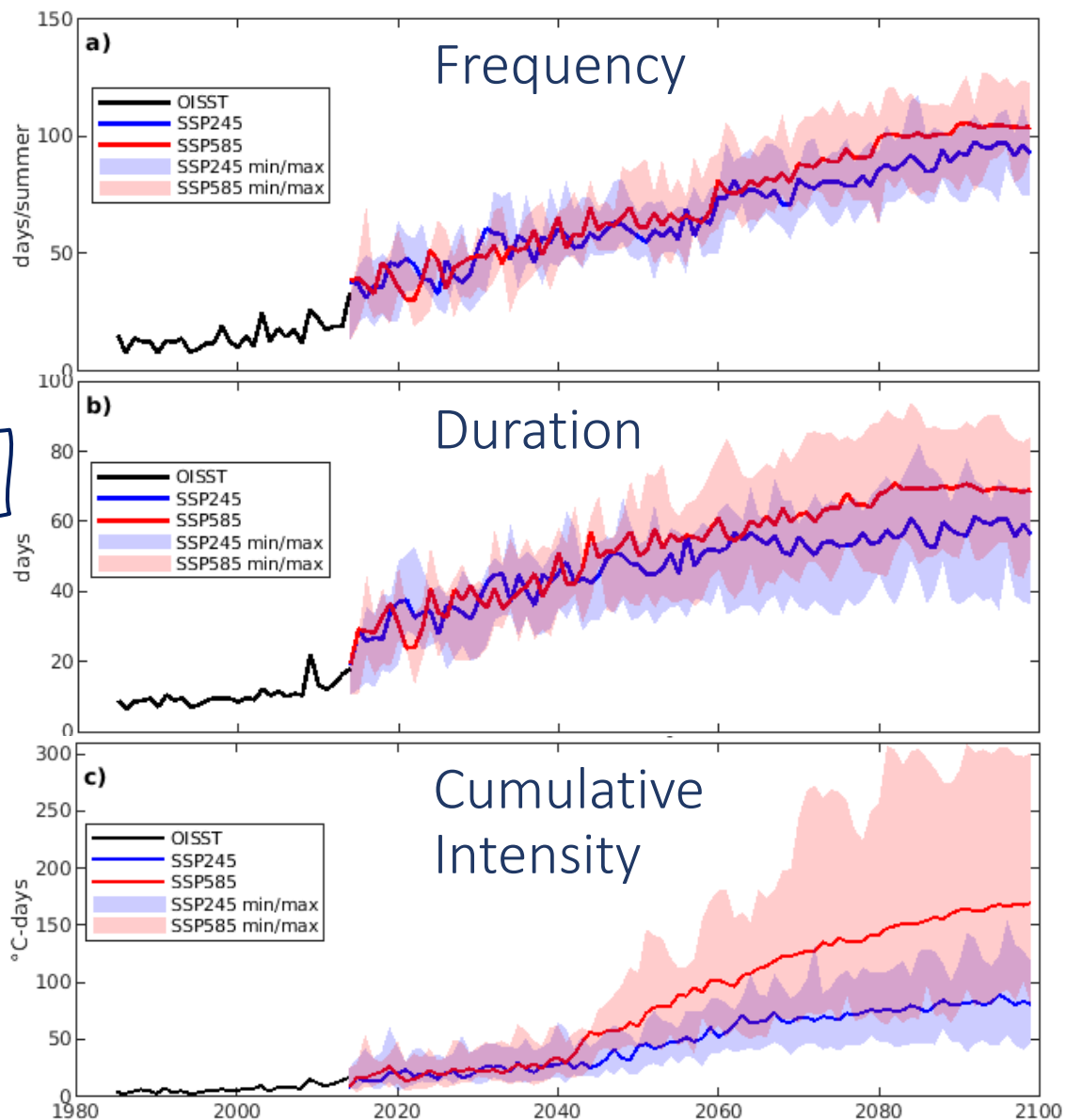
Extension



+7%



Compound Events



CMIP6

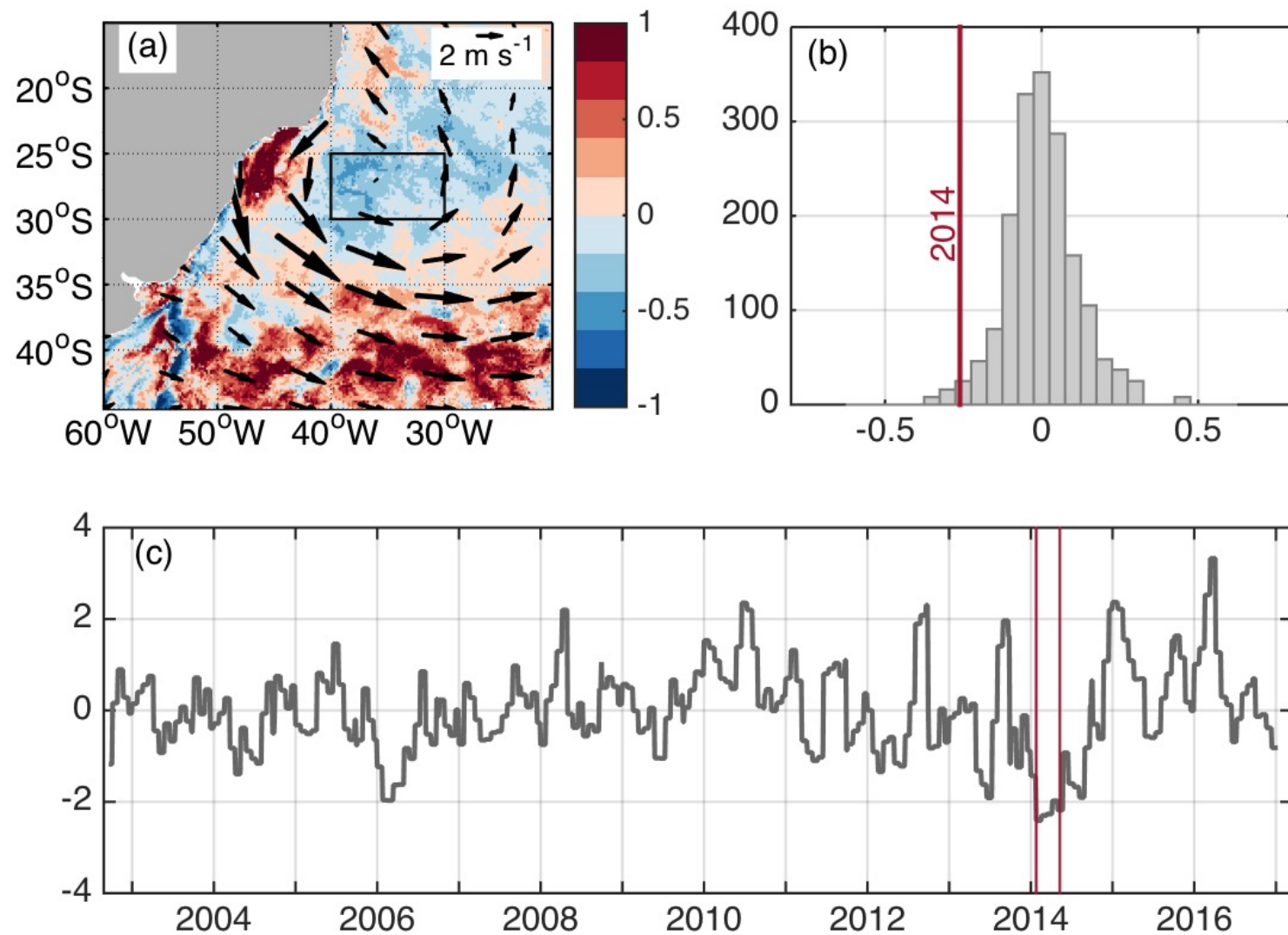
- ✓ The frequency, duration and intensity of marine heatwaves will **significantly increase** for the next decades in the western South Atlantic.
- ✓ The greatest trends in the marine heatwave characteristics occur during **the period of 2021–2050** and not by the end of the 21st century.
- ✓ The future trends are driven by the long-term warming and the **intensification of atmospheric blocking** over the region.
Costa & Rodrigues (2021, GRL)



Compound Events

Land-Ocean Compound

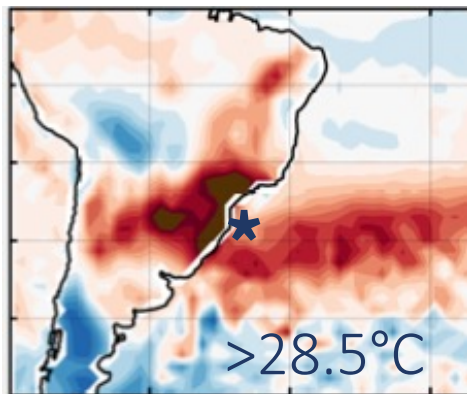
Ocean Colour
Impact (mg/m^3)





Compound Events

Land-Ocean Compound



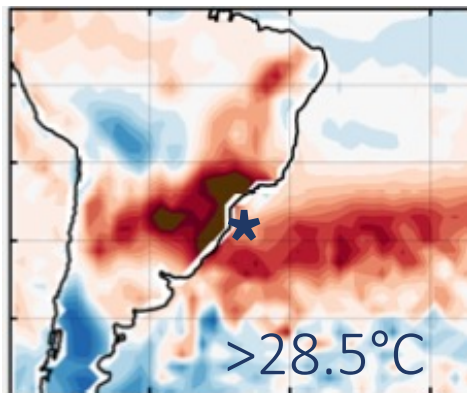
Clam - Vongole
(*Anomalocardia flexuosa*)





Compound Events

Land-Ocean Compound



Oyster
(*Crassostrea giga*)

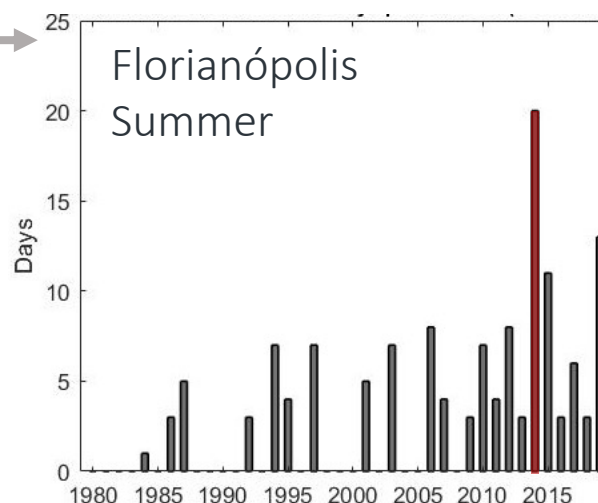
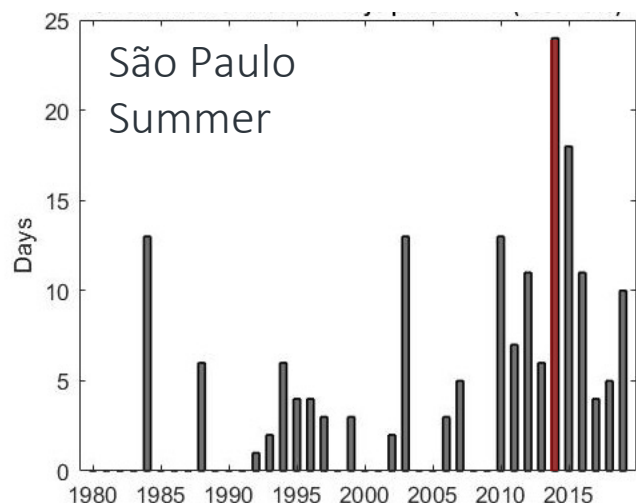
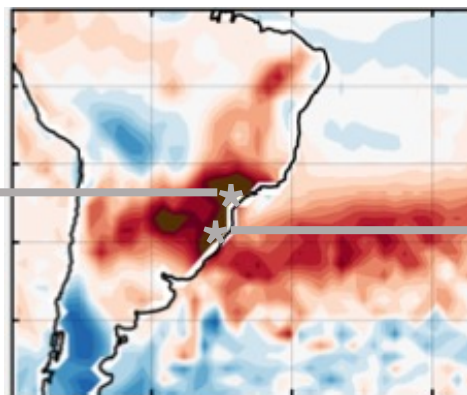
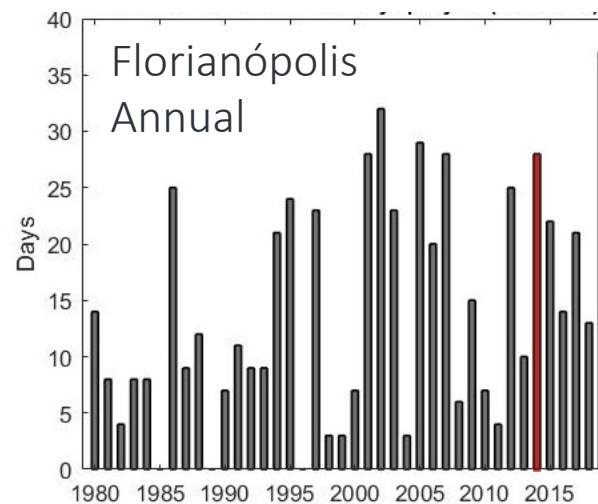
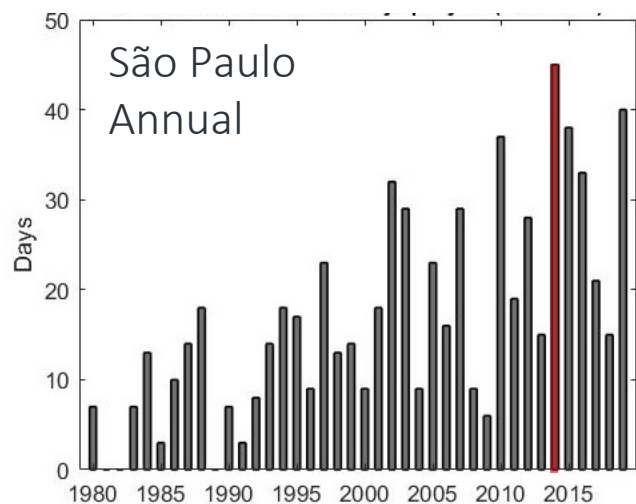




Compound Events

Land-Ocean Compound

Heatwaves



Methodology by Perkins & Alexander (2013)



Compound Events

Land-Ocean Compound



50 MIL ATINGIDOS
Governo decreta racionamento de água

O governador Wellington Dias (PT) decretou o racionamento de água na região de São João del-Rei, em Minas Gerais, em setembro de 2017. O racionamento afetará 50 mil habitantes de 130 bairros da região. O governador anunciou que o racionamento será de 10 minutos por dia, de segunda a sexta-feira, das 6h às 18h. O racionamento será de 10 minutos por dia, de segunda a sexta-feira, das 6h às 18h. O racionamento será de 10 minutos por dia, de segunda a sexta-feira, das 6h às 18h.

BARRAGEM PIMAS está com apenas 3% de sua capacidade

Barragem de Pimás, que tem apenas 3% de sua capacidade de armazenamento de água. O governador anunciou que o racionamento será de 10 minutos por dia, de segunda a sexta-feira, das 6h às 18h.

Novo de Pimás, Campo Grande, além do povoado Manocara, de armazenamento de água. O governador anunciou que o racionamento será de 10 minutos por dia, de segunda a sexta-feira, das 6h às 18h.

EM BAIXA

Sem racionamento de energia, reservatórios do país estão abaixo do desejado



Bacias da região Sudeste/Centro-Oeste representam 70% da capacidade de armazenamento



Historicamente, os níveis destes reservatórios nunca fecharam o mês de setembro abaixo de 30%

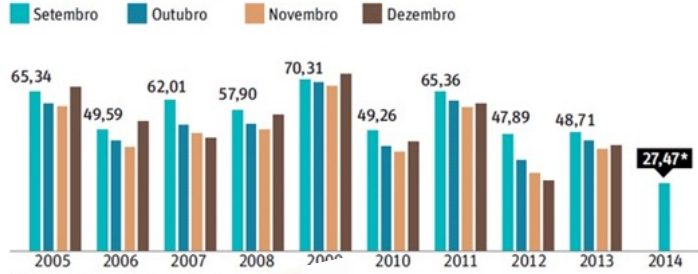


Governo previa chegar a novembro (fim da seca) com reservatórios entre 30% e 40% cheios, para garantir reabastecimento



Com níveis abaixo da meta, previsão é que o país fique muito dependente do próximo regime de chuvas, com risco ao abastecimento

Histórico do nível de água, em %



*Resultado parcial, verificado em 17 de setembro de 2014. Fonte: ONS



Crise exige novos hábitos

Momento impõe revisão das rotinas e atitudes em casa, nas finanças e no trabalho

Mude o comportamento

Não desperdice comida

Compostível

Economize energia

Evite desperdício de água

TV e cabo

Renegocie

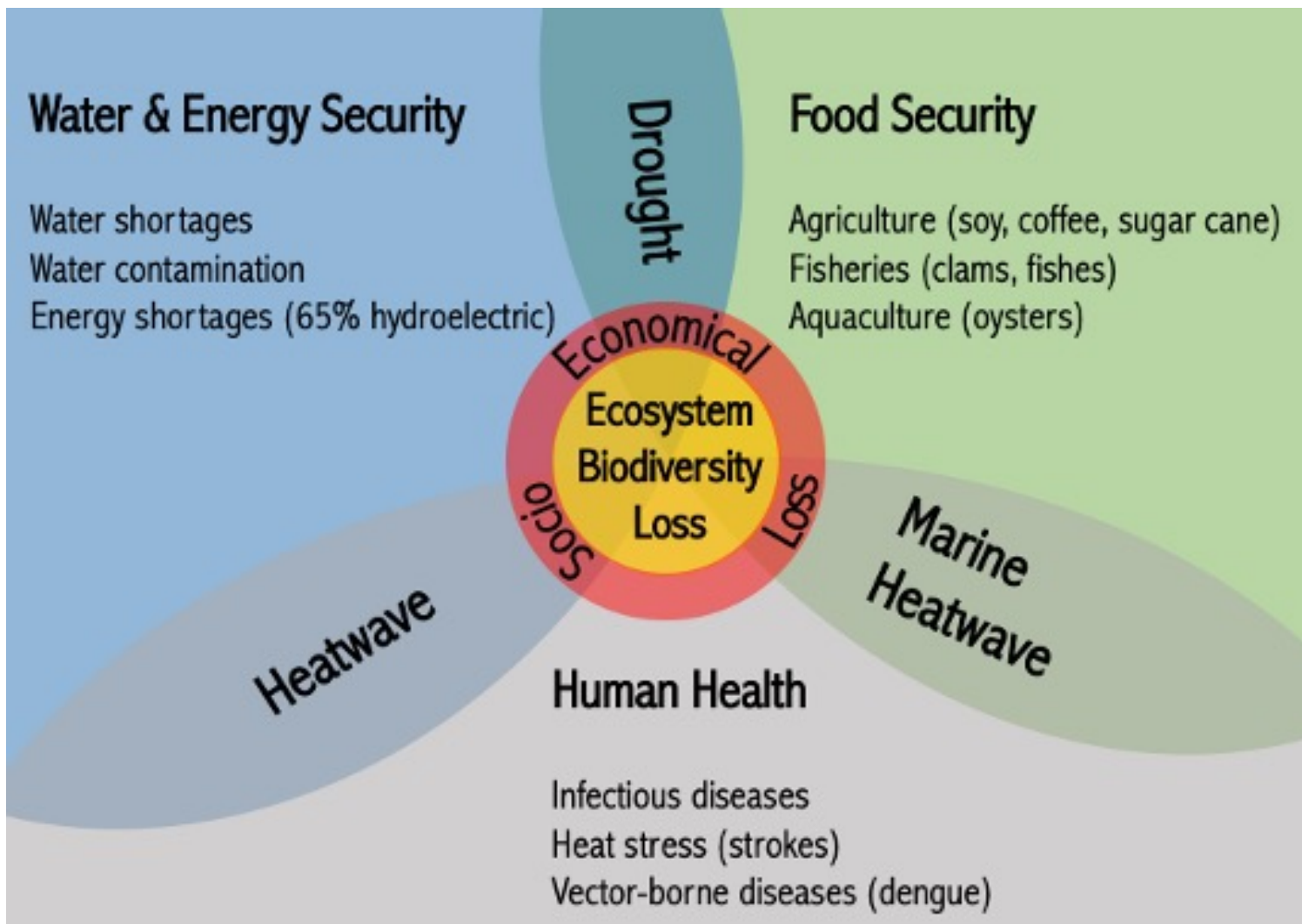
Faça a diferença no trabalho

Demostre sua capacidade



Compound Events

Land-Ocean Compound

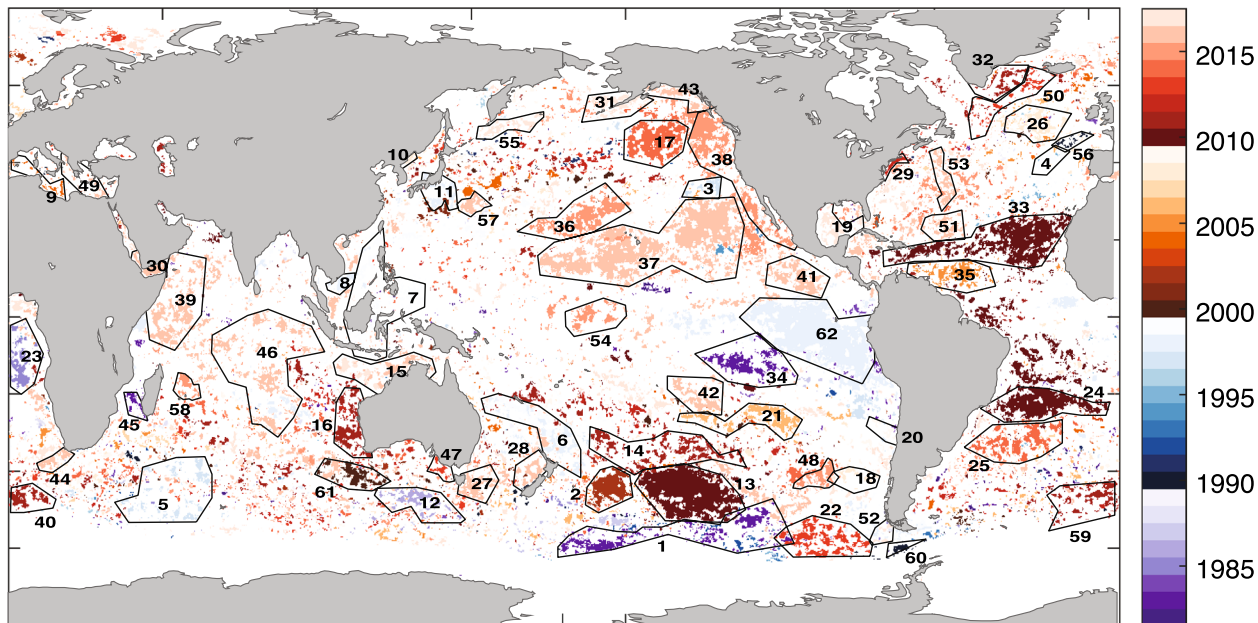




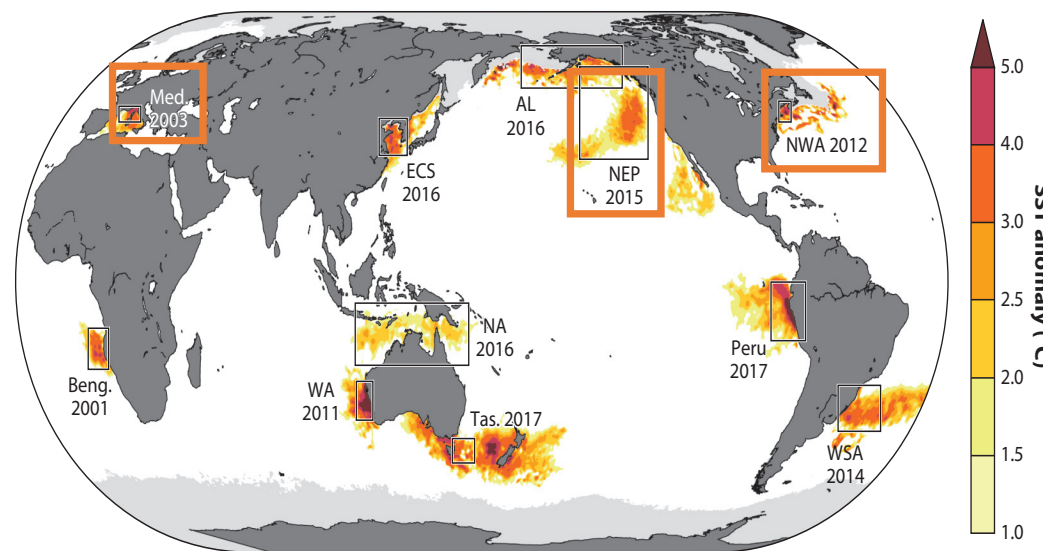
Compound Events

Land-Ocean Compound

Strongest and longest recorded MHW



✓ Similar drivers and impacts
Sen Gupta et al. (2020, Sci. Rep.)



- ✓ Mediterranean Sea 2003
- ✓ Northwest Atlantic 2012
- ✓ Northeast Pacific 2015 = The Blob



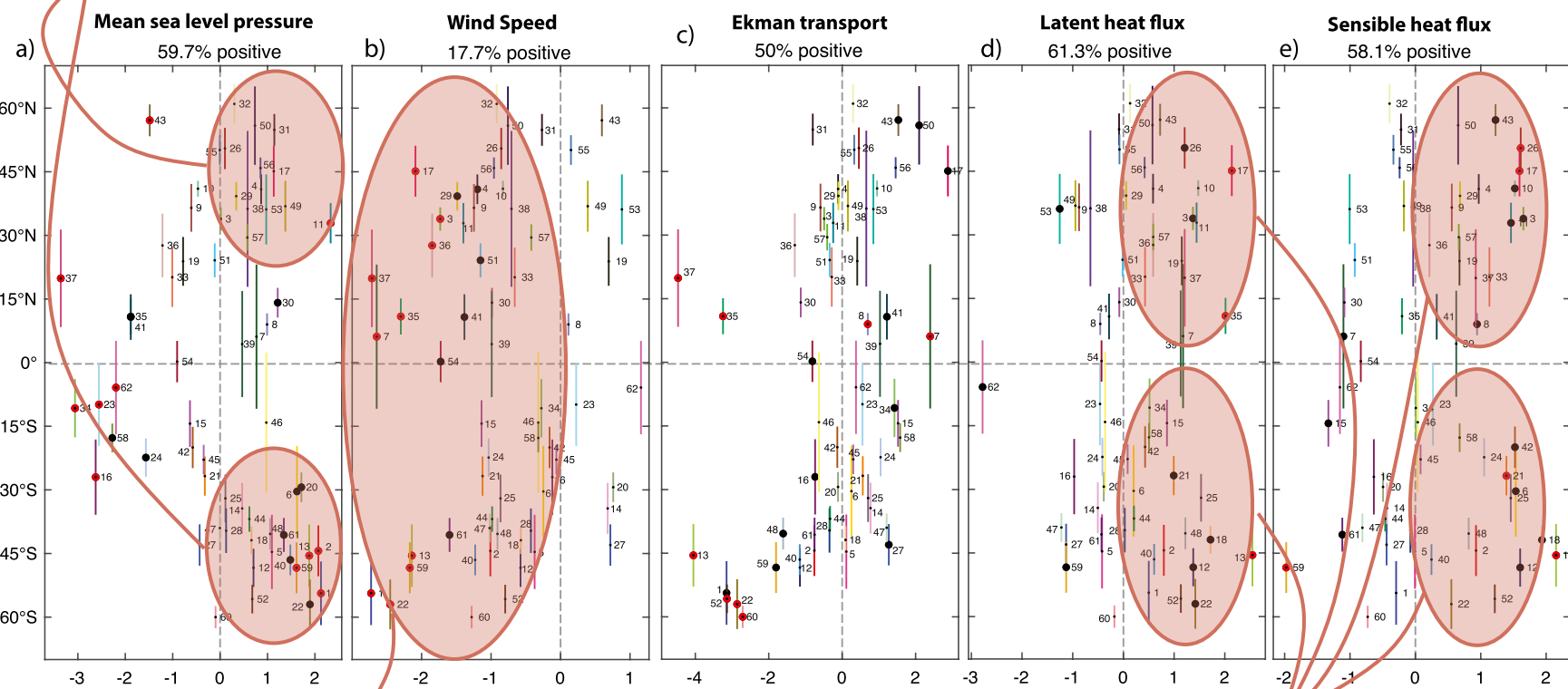
Compound Events

Land-Ocean Compound

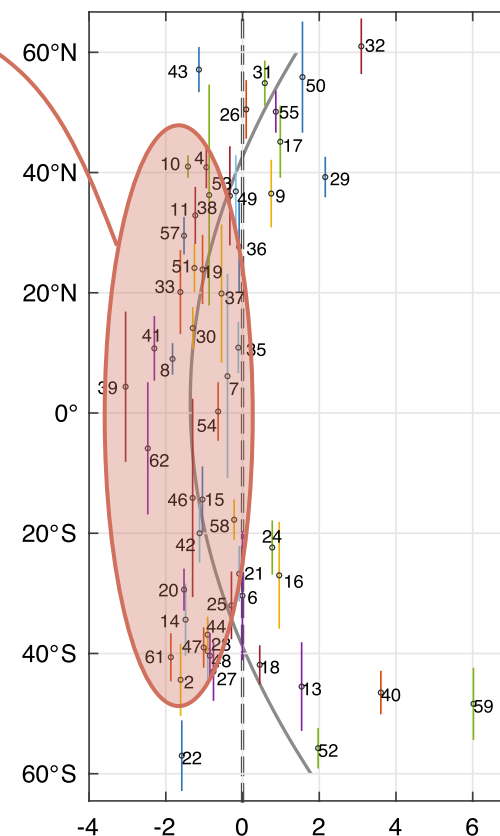
Sen Gupta et al. (2020, Sci. Rep.)

1 Almost all extratropical MHW associated with **high-pressure systems**

4 **Reduced productivity** at lower latitudes



Normalized chl-a anomalies by latitude



2 Almost all MHW associated with **weak winds**

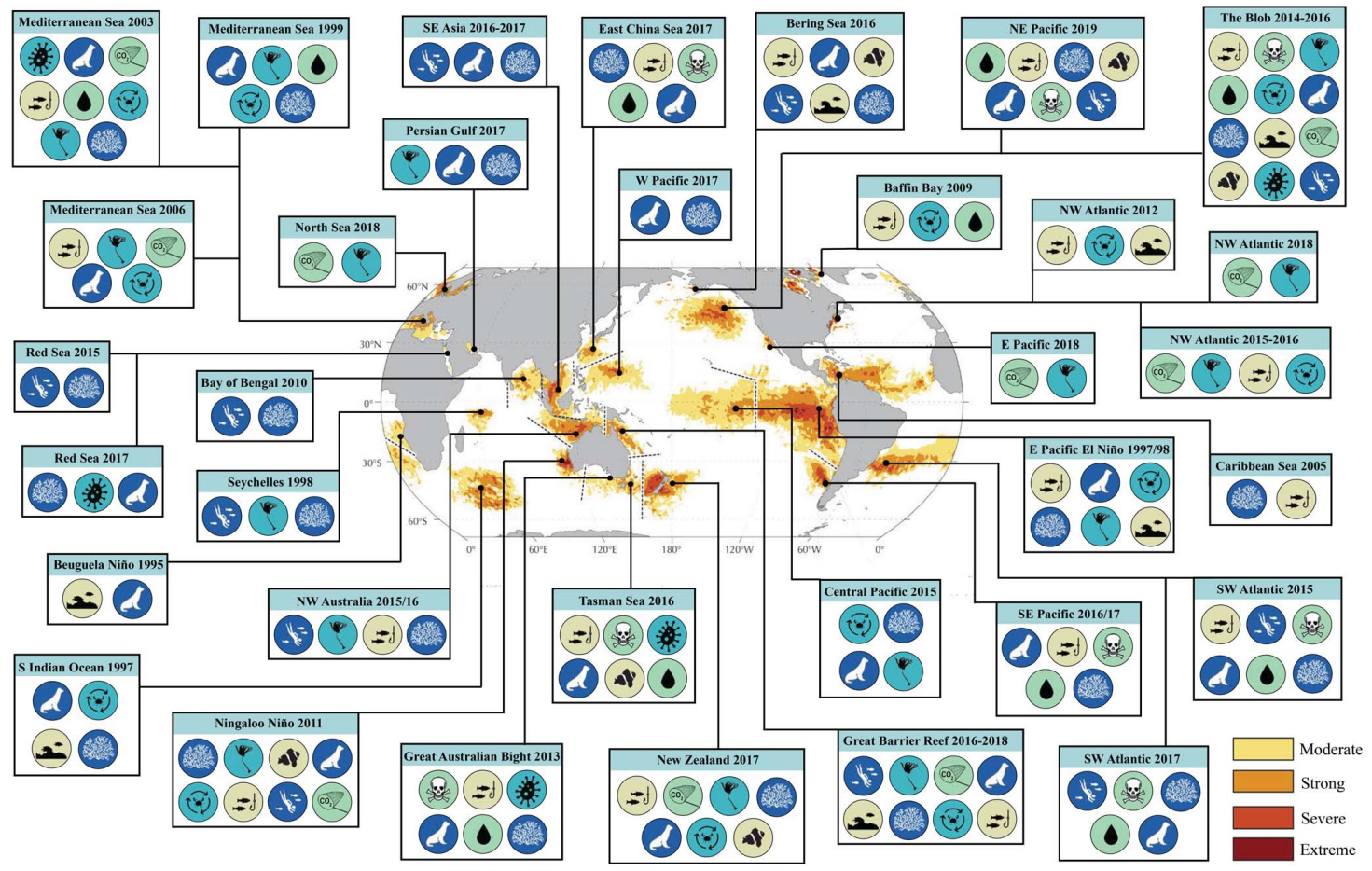
3 Many MHW associated with **weaker evaporative (sensible) cooling**

Standard deviations



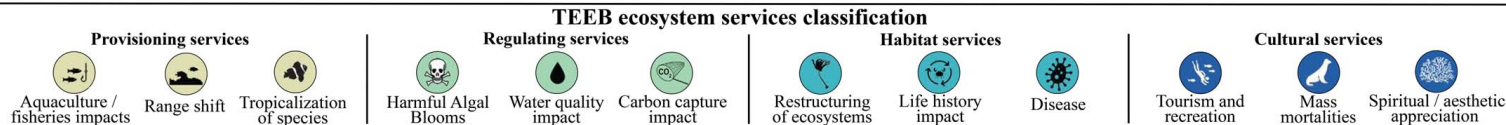
Compound Events

Land-Ocean Compound



“Reported economic costs of individual MHW events exceed US\$800 million in direct losses or >US\$3.1 billion in indirect losses of ecosystem services for multiple years.”

Smith et al. (2021, Science)





Compound Events

Ocean Compound

- ✓ Marine **Heatwaves**
- ✓ Extremes of High **Acidity**
- ✓ Extremes of Low **Oxygen**
- ✓ Extremes of Low **Productivity**

nature

Biogeochemical extremes and compound events in the ocean

Nicolas Gruber , Philip W. Boyd, Thomas L. Frölicher & Meike Vogt

nature communications

Compound marine heatwaves and ocean acidity extremes

Friedrich A. Burger , Jens Terhaar & Thomas L. Frölicher

Warm
waters



[H⁺] via changes in the carbonate chemistry equilibrium



O₂ via reduction of solubility in surface waters



Primary productivity via reduction of nutrients



Compound Events

Ocean Compound

Baseline 1982-2020

Hobday et al. (2016, Prog. Oceanogr.)

Marine Heatwaves (MHW)

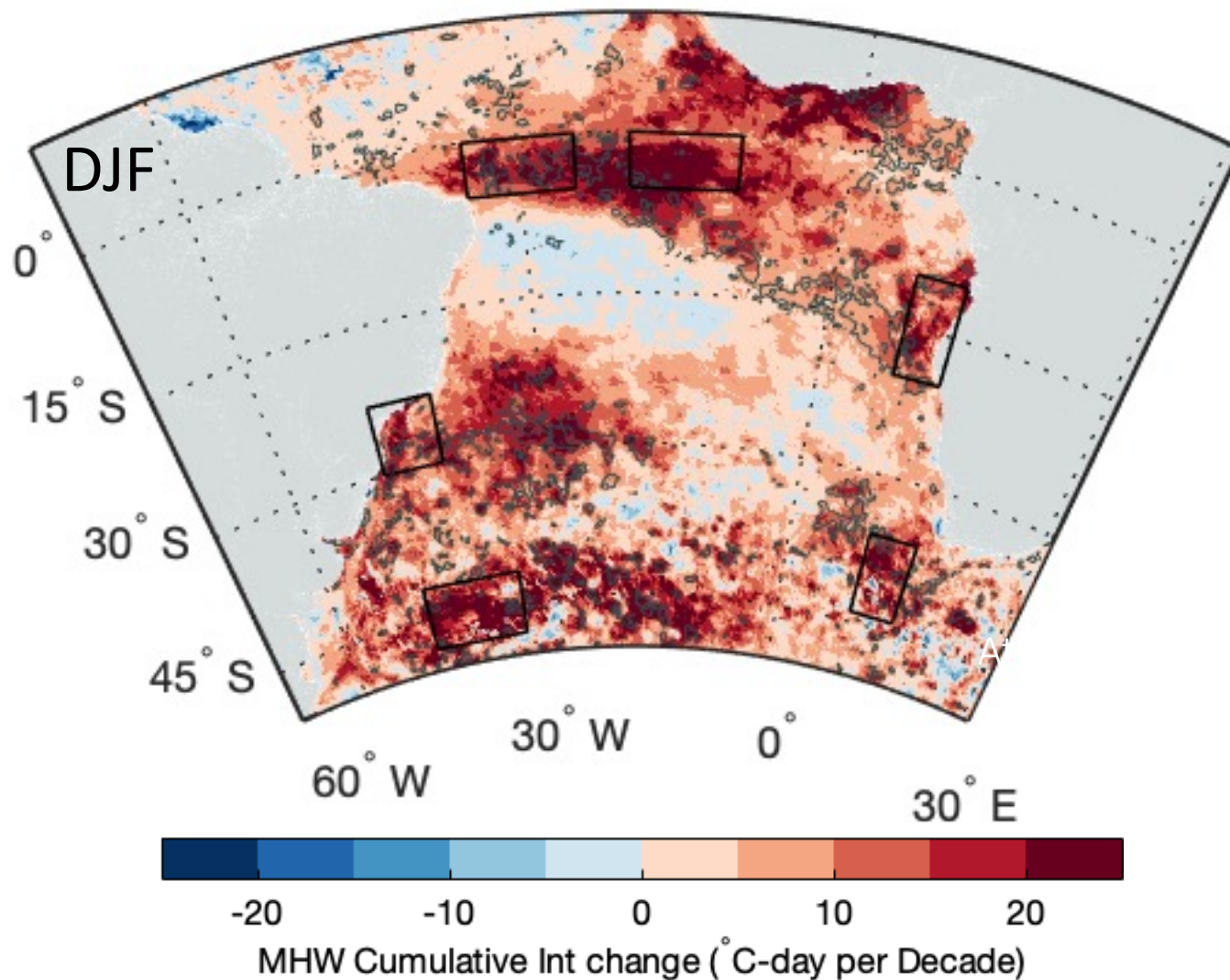
cumulative intensity

$\approx \sum$ daily intensity anomalies

Thomas Frölicher
Friedrich Burger

Noel Keenlyside
Alistair Hobday

Trends (1982-2020)





Compound Events

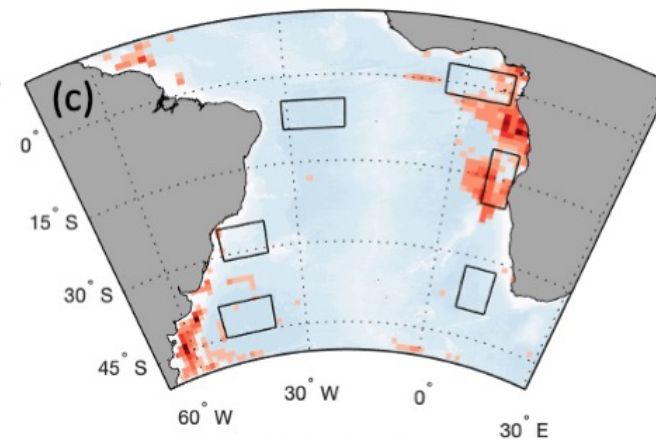
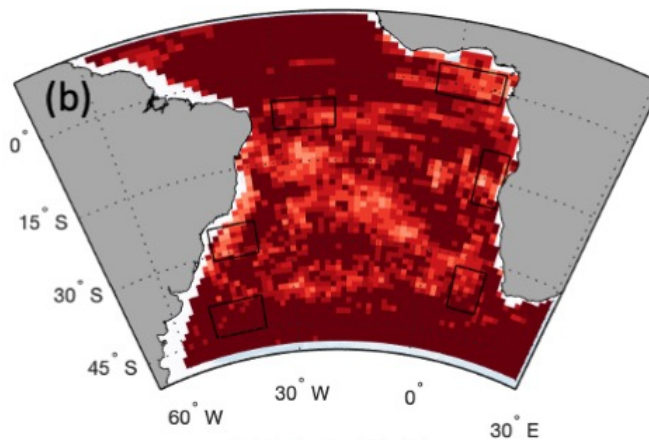
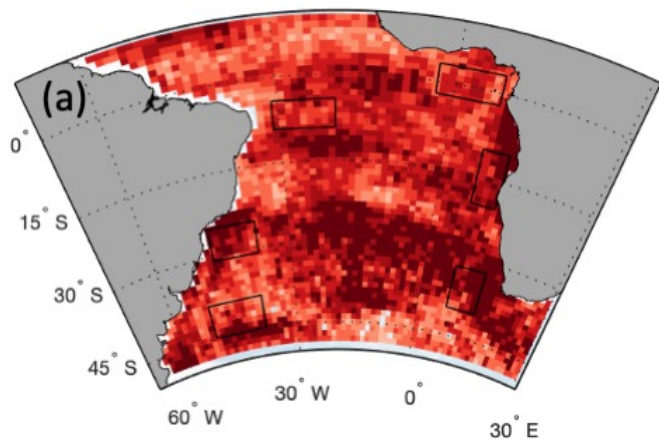
Ocean Compound

MHW

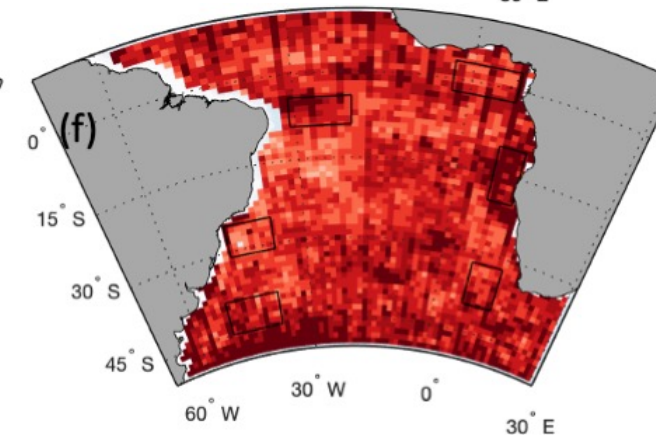
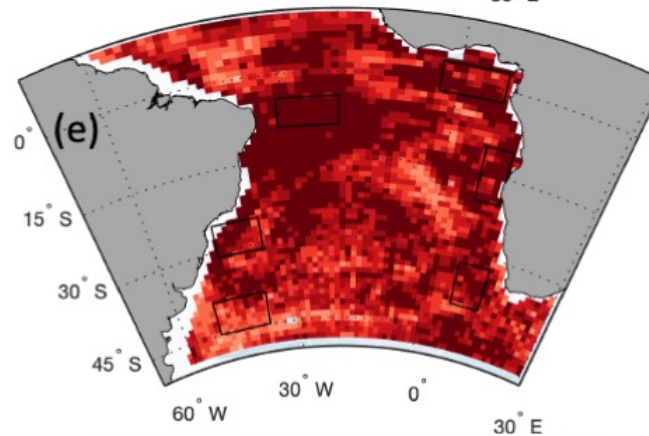
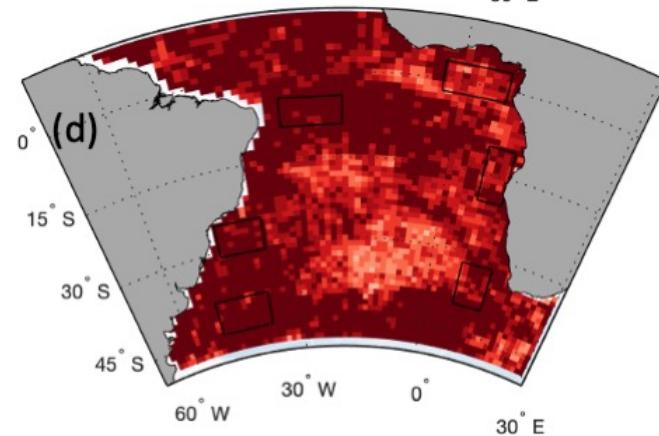
Low Chlorophyll

High Acidity

1999-2008



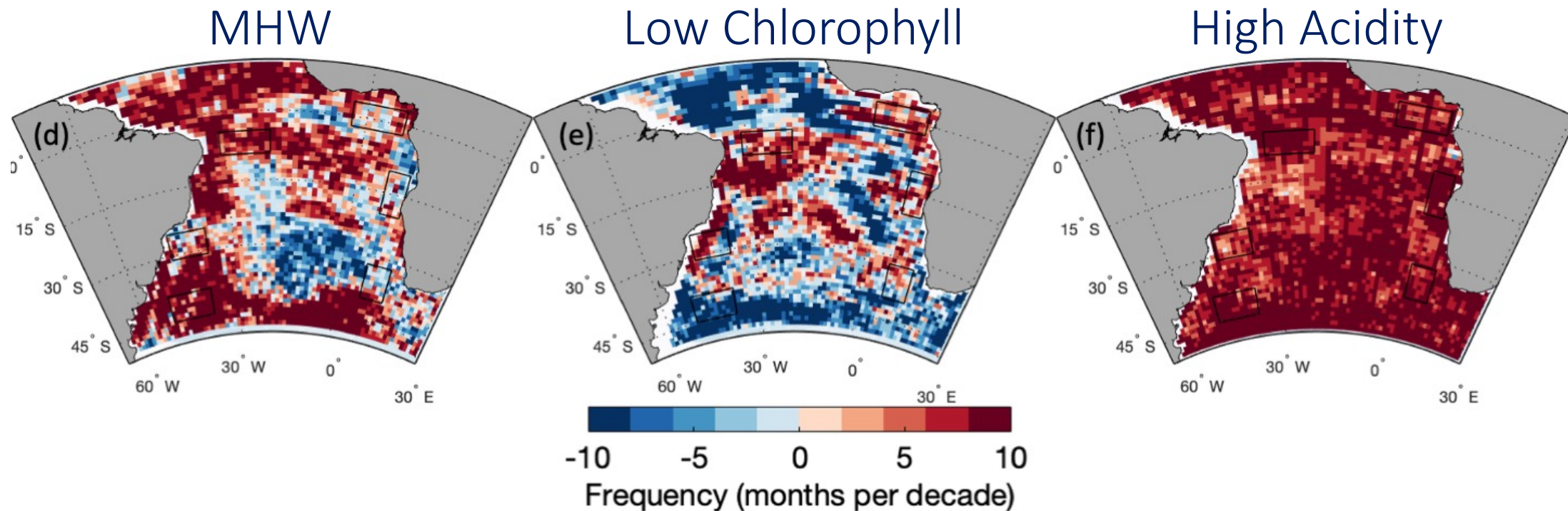
2009-2018





Compound Events

Ocean Compound



(2009-2018) – (1999-2008)



Compound Events

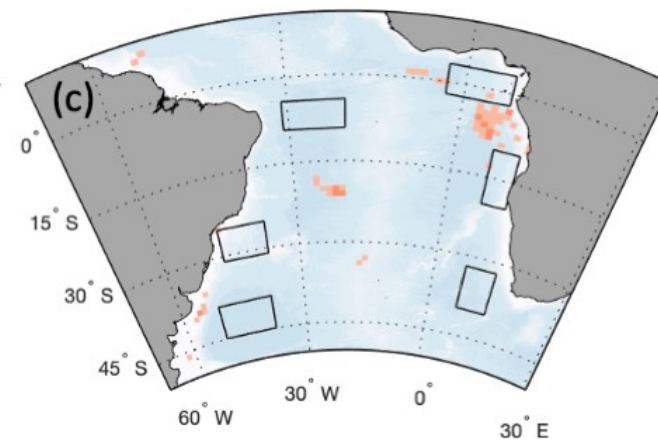
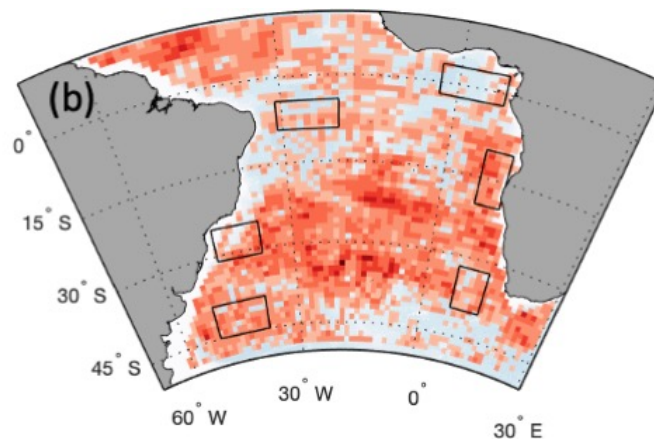
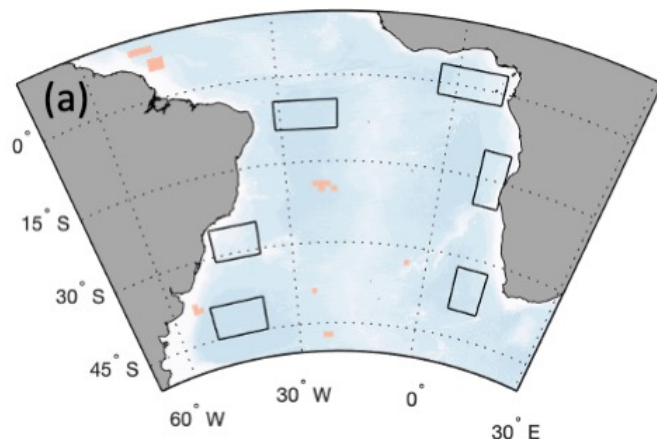
Ocean Compound

MHW + LC + HA

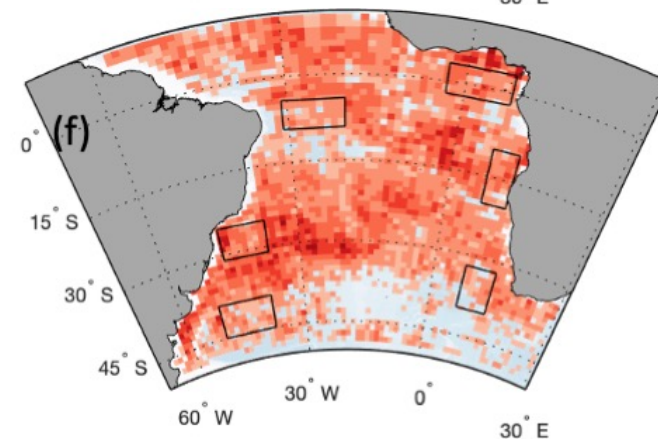
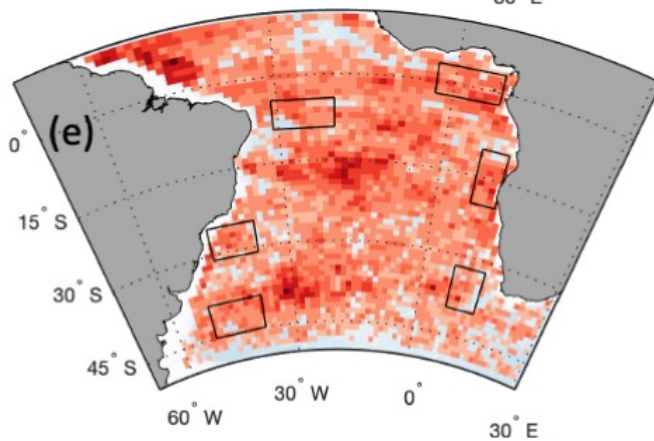
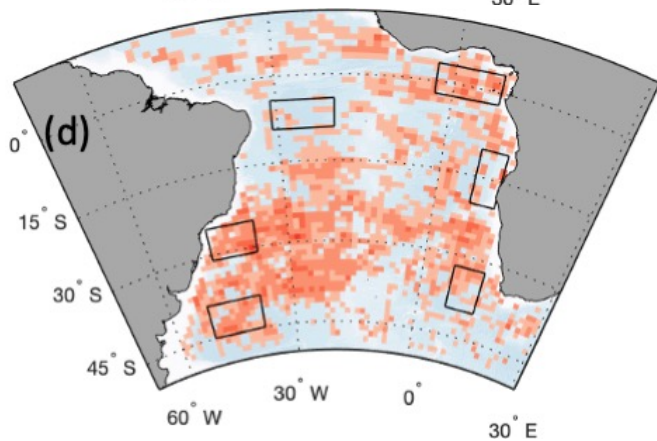
MHW + LC

MHW + HA

1999-2008



2009-2018



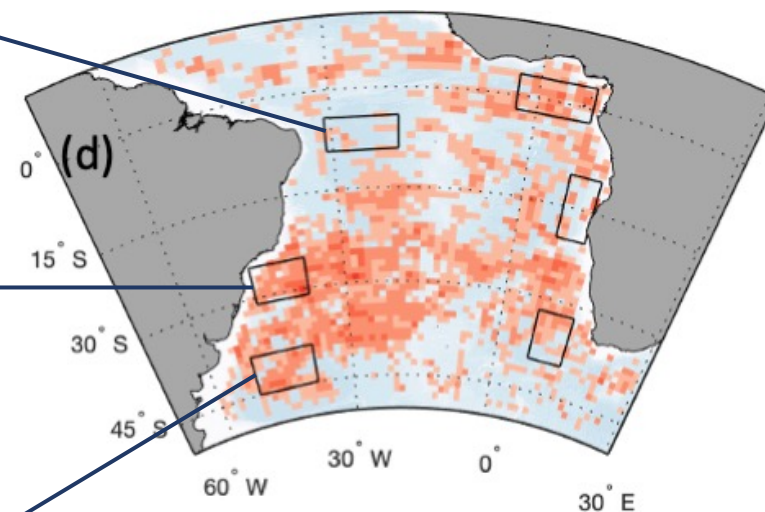
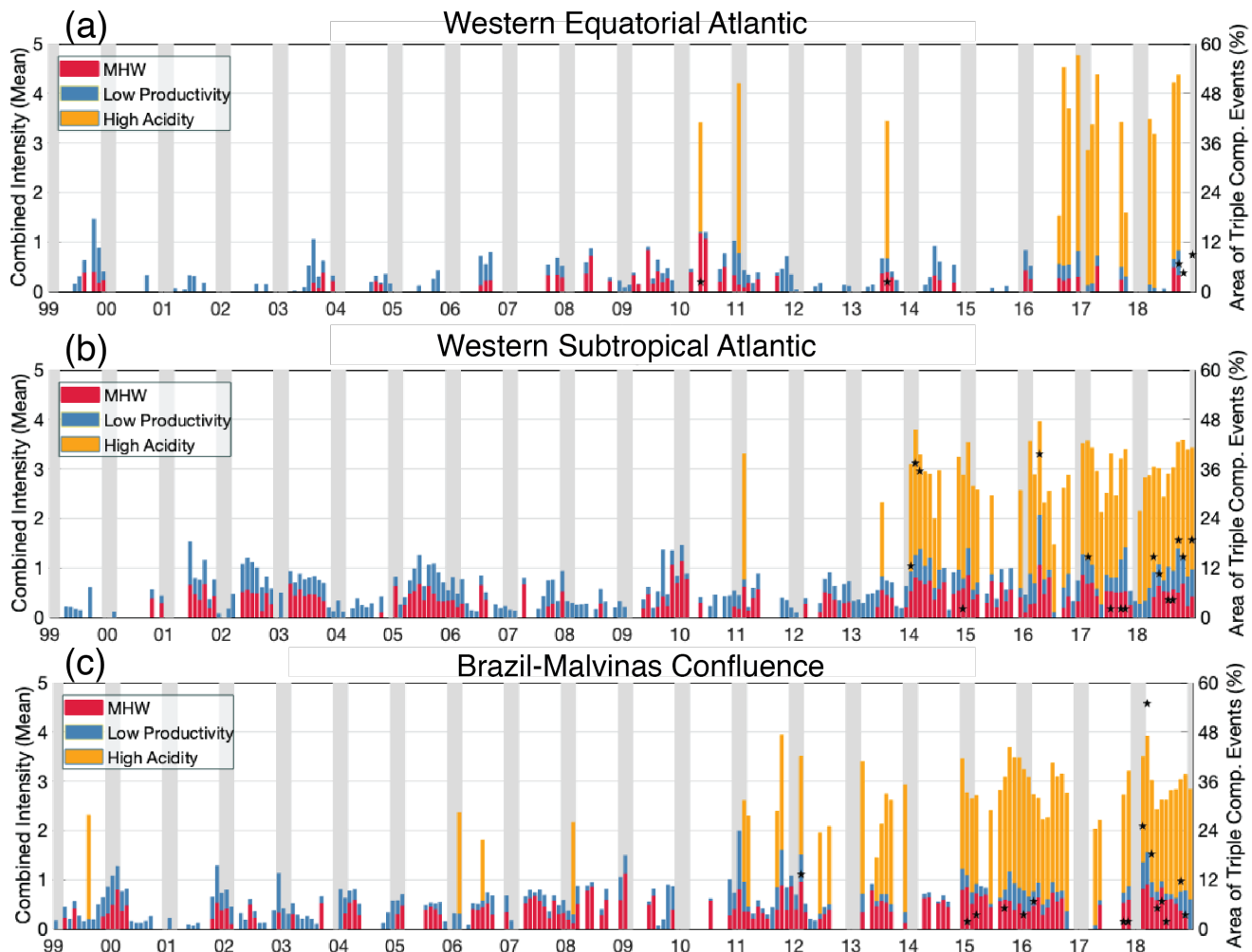
LC = Low Chlorophyll
HA = High Acidity





Compound Events

Triple Compound: MHW + Low Chlorophyll + High Acidity

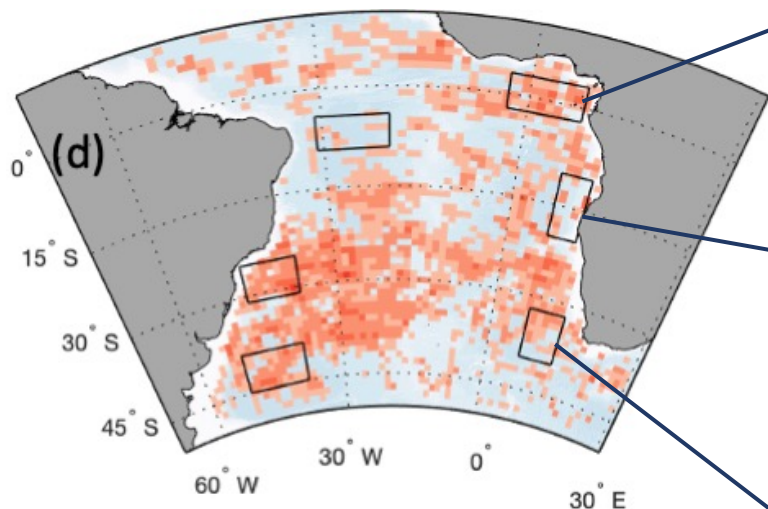


Values displayed are normalised by their standard deviation. Asterisks indicate the area simultaneously covered by the triple compound in each region (in percentage, right y-axis)

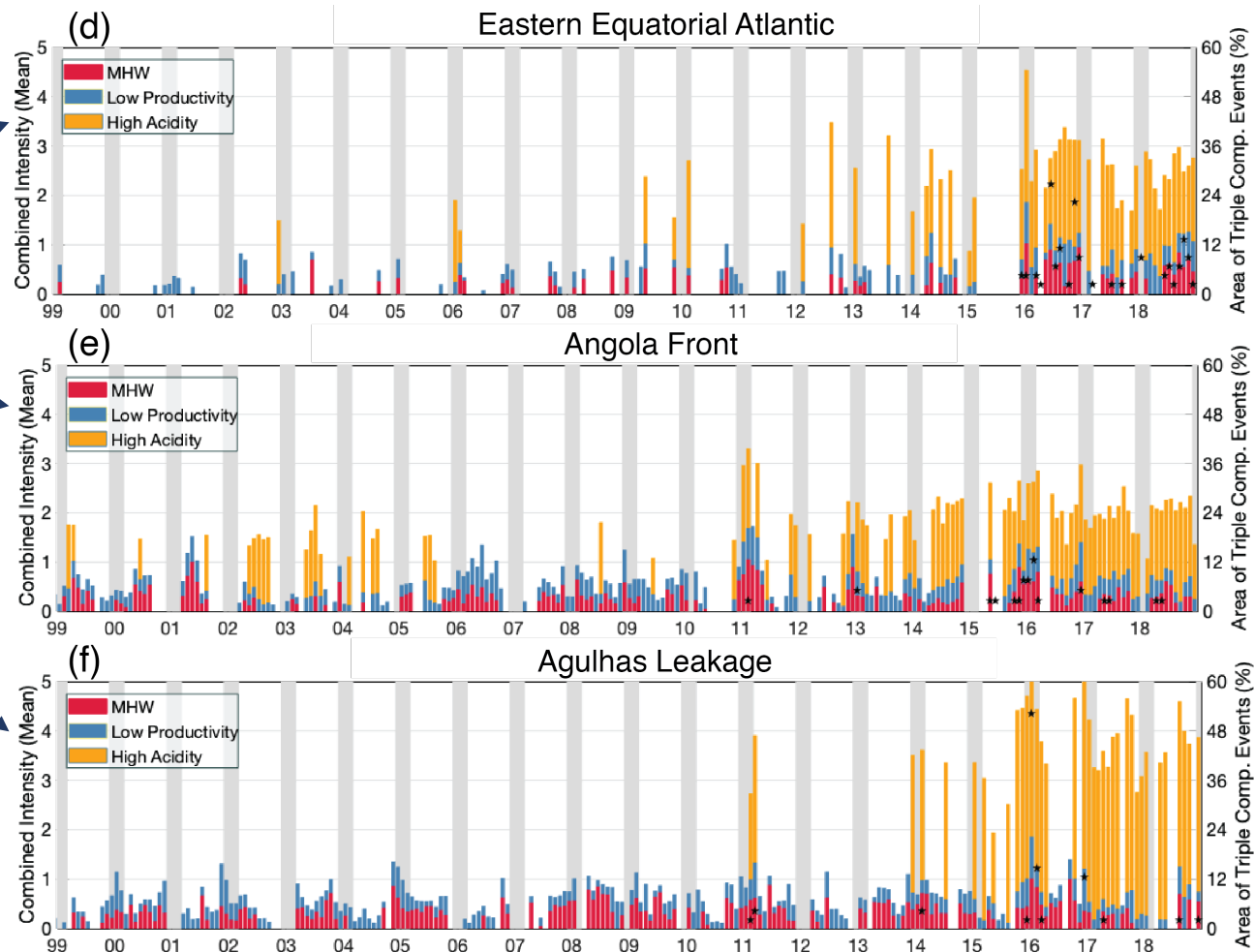


Compound Events

Triple Compound: MHW + Low Chlorophyll + High Acidity



Values displayed are normalised by their standard deviation. Asterisks indicate the area simultaneously covered by the triple compound in each region (in percentage, right y-axis)





Compound Events

Ocean Compound

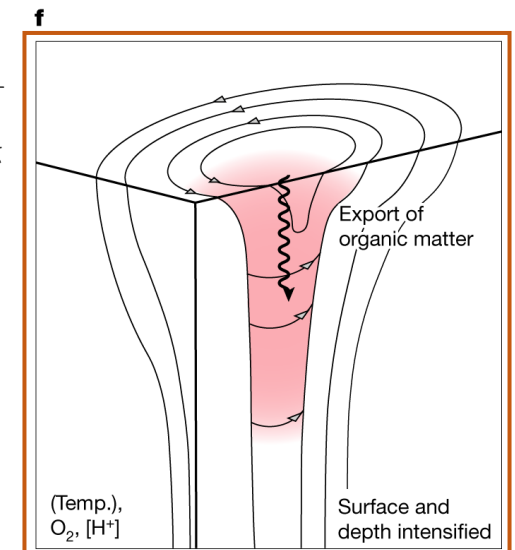
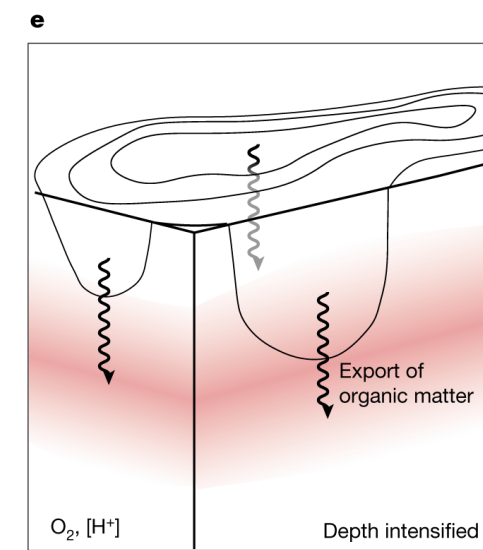
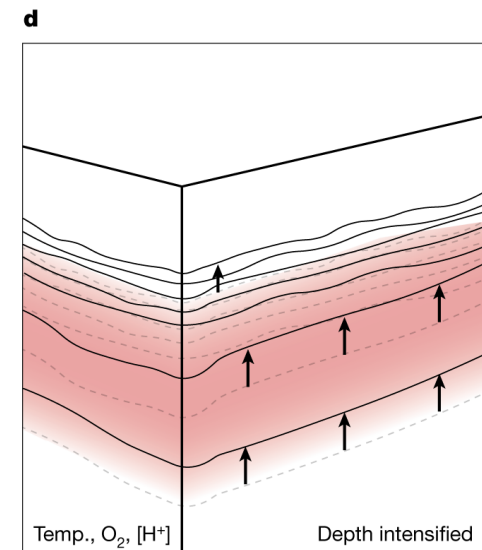
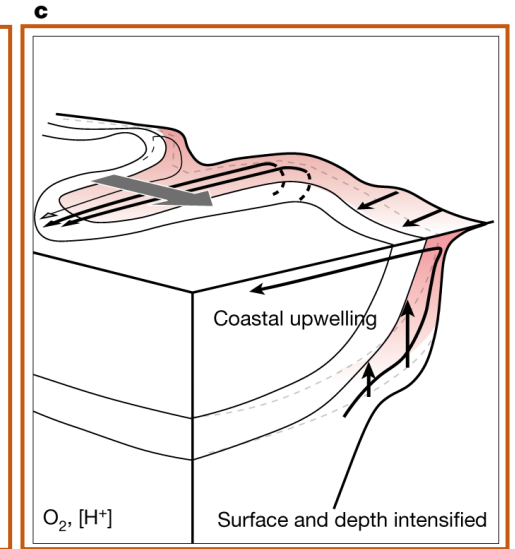
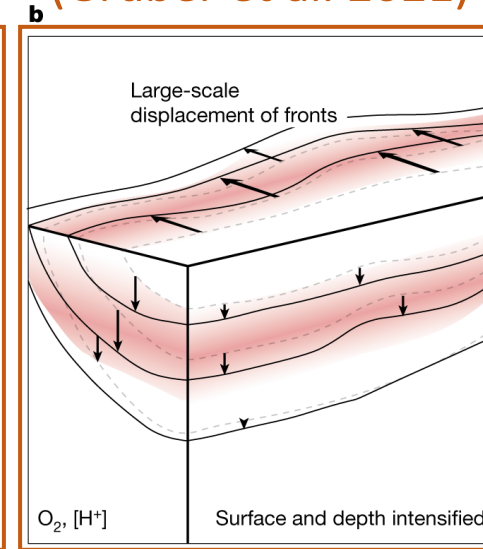
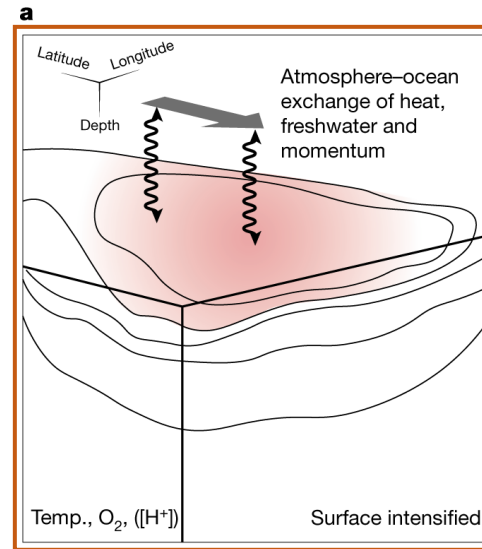
(a) **Air-sea Interaction:** Western Equatorial and Subtropical Atlantic

(b) **Front Displacement:** Angola and Brazil-Malvinas Confluence

(c) **Upwelling:** Eastern Equatorial Atlantic and Angola Front

(f) **Eddie Trapping:** Agulhas Leakage

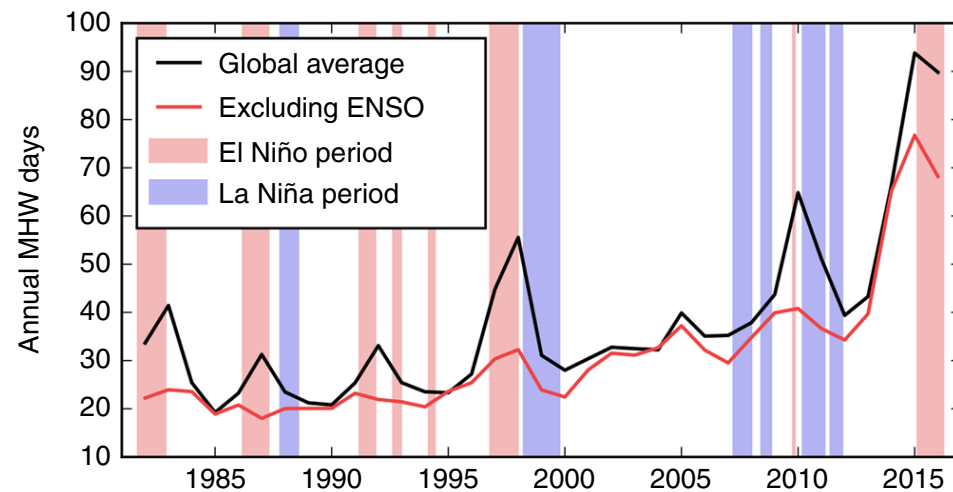
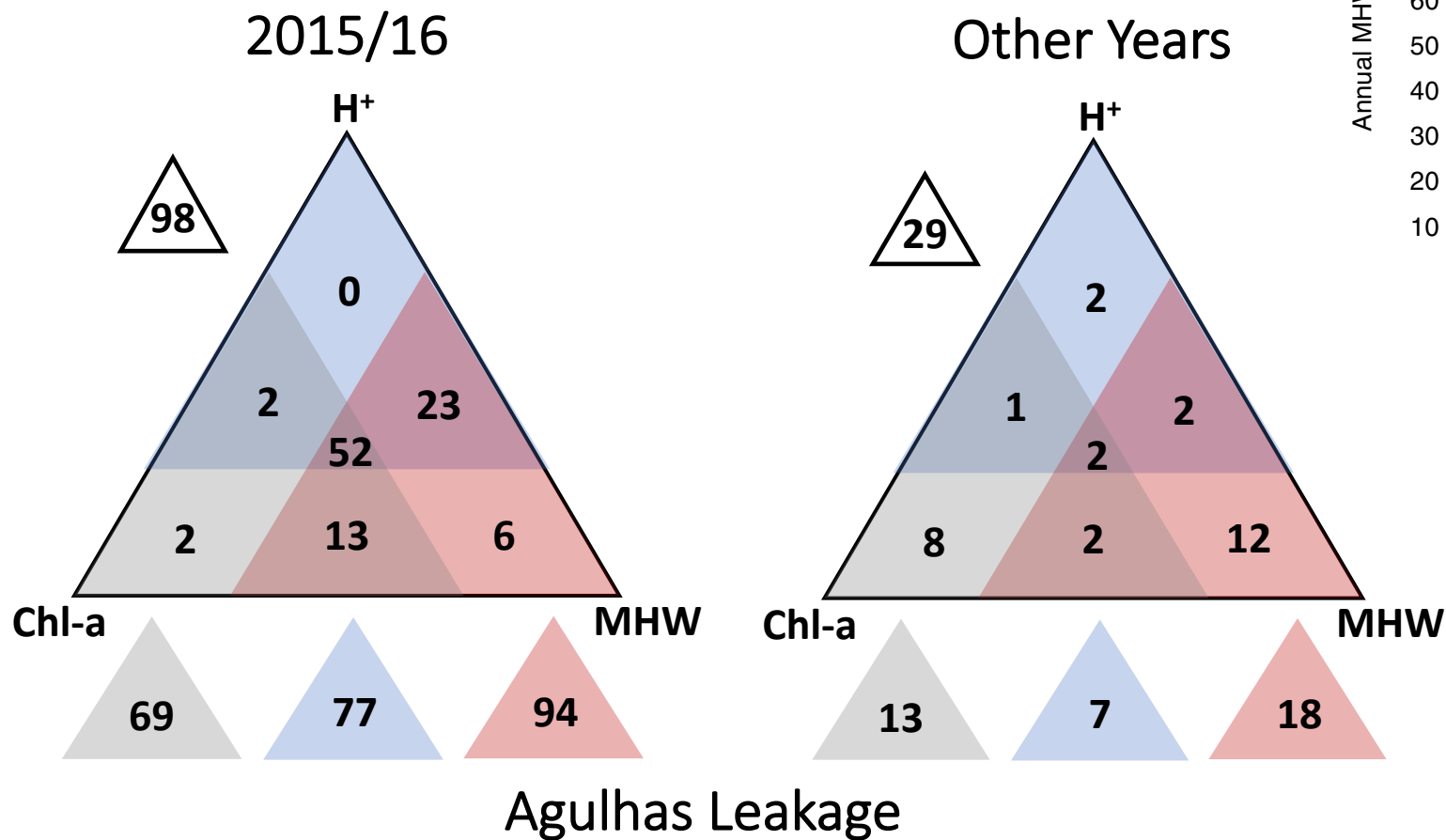
(Gruber et al. 2021)





Compound Events

Ocean Compound

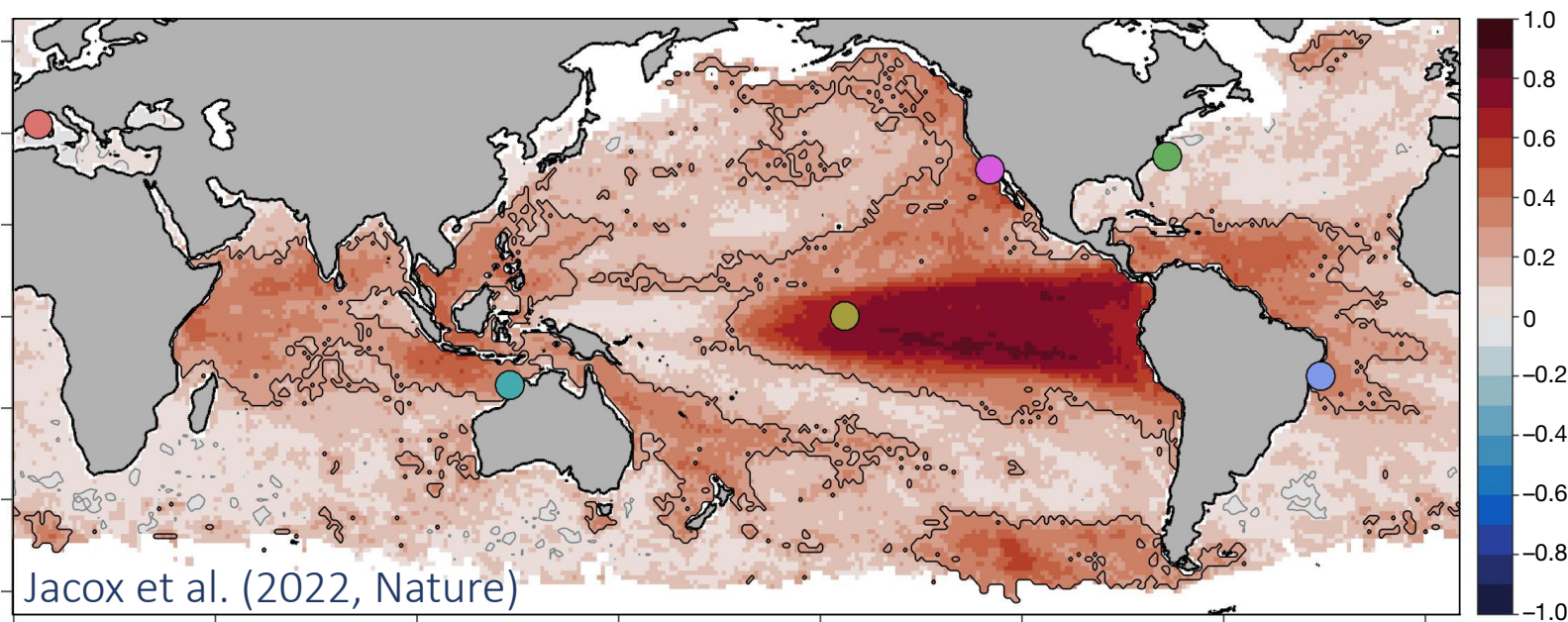


Oliver et al. (2018, Nat. Comm.)



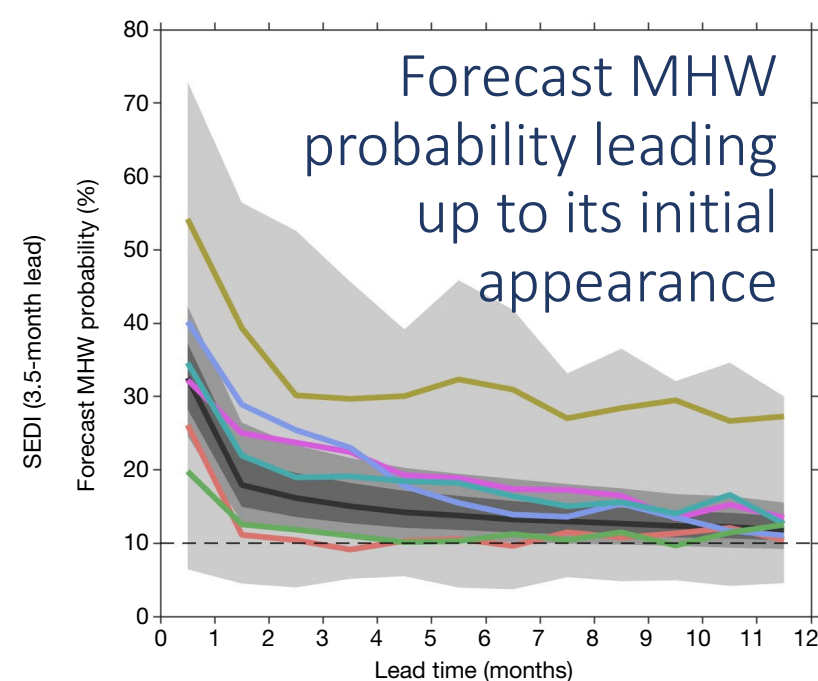
Compound Events

Seasonal Forecasts



Jacox et al. (2022, Nature)

MHW forecast skill with lead time of 3.5 months



Successful **adaptation** depends greatly on effective forecast

Compound extremes – offer an opportunity to advance our knowledge about MHW



Compound Events

Implication



- ✓ Ocean warming combined with acidification can **negatively affect** many species' survival, growth, development and shifts in community structure



- ✓ Several studies show that their negative impact can be **mitigated** by an increase in food availability



- ✓ However, this is not possible when compound extremes of warming and high acidity **co-occur with low chlorophyll** concentrations, i.e., a decrease in food availability



Compound Events

Gaps & Opportunities



Land and ocean compound extremes need to be **considered together**



They often have the **same drivers**, and our knowledge of land extremes is more advanced



Their **compound impacts** can be nonlinear, amplifying socioeconomic losses



The challenge of (ocean) **data restriction**

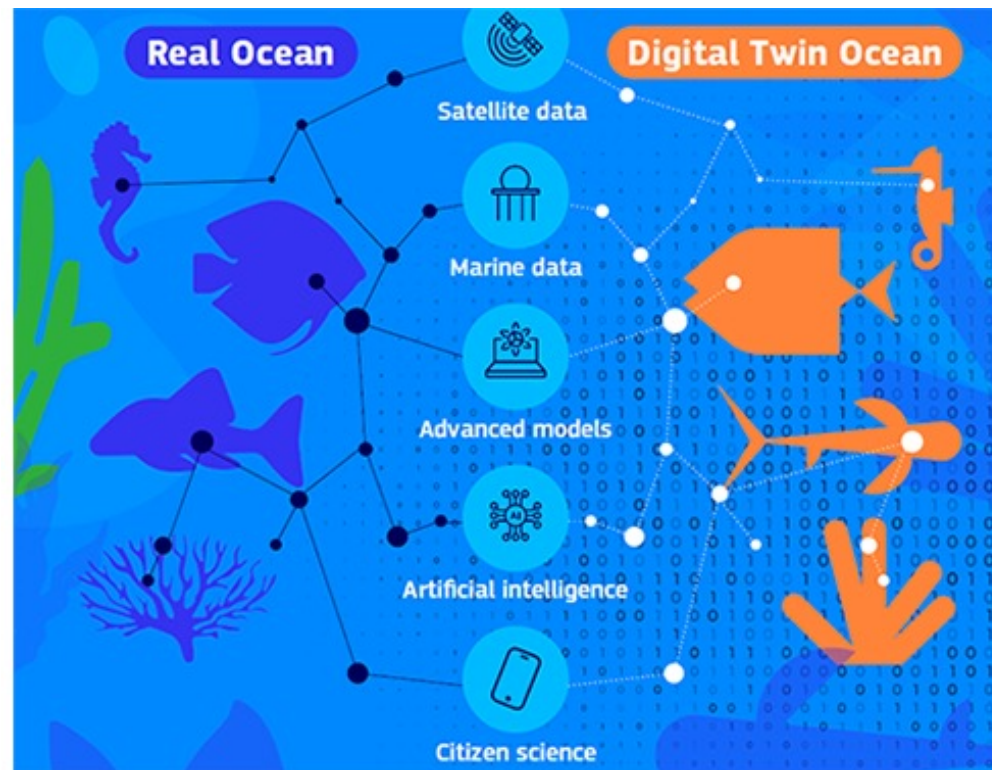


Achievable for **regional studies**



Compound Events

Gaps & Opportunities



Digital Earth is a concept of an interactive digital replica of the entire planet that can facilitate a shared understanding of the multiple relationships between the physical and natural environments and society.



Compound Events

Gaps & Opportunities



Small is beautiful: climate-change science as if people mattered 🗝

Regina R Rodrigues, Theodore G Shepherd ✉

PNAS Nexus, Volume 1, Issue 1, March 2022, pgac009,

<https://doi.org/10.1093/pnasnexus/pgac009>

Traditional ways of producing aggregated climate information can leave climate scientists empty-handed for many regions of the world

Yet there can be a wealth of local climate knowledge (e.g. Chapter 10 of IPCC AR6)

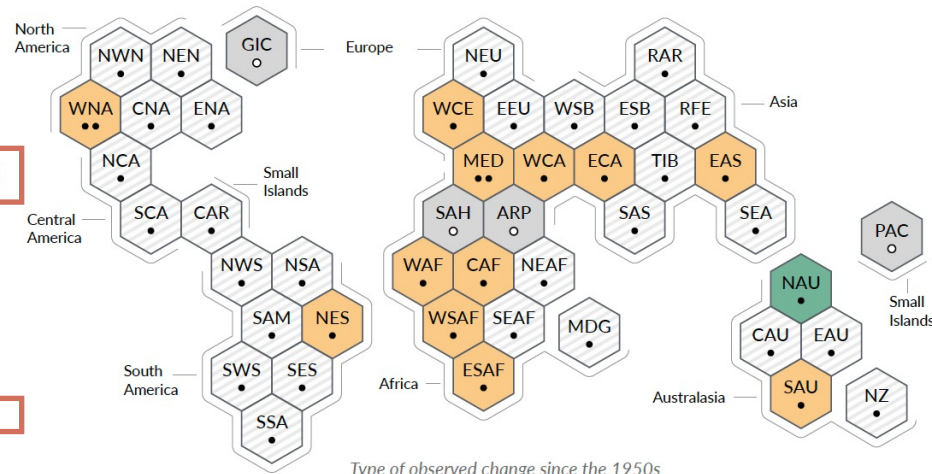
c) Synthesis of assessment of observed change in **agricultural and ecological drought** and confidence in human contribution to the observed changes in the world's regions

Type of observed change in agricultural and ecological drought


- Increase (12)
- Decrease (1)
- Low agreement in the type of change (28)
- Limited data and/or literature (4)

Confidence in human contribution to the observed change

- High
- Medium
- Low due to limited agreement
- Low due to limited evidence



Type of observed change since the 1950s



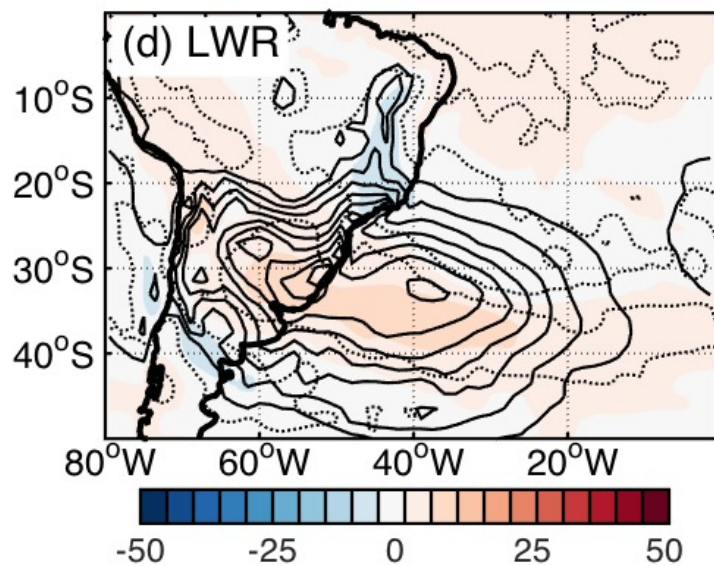
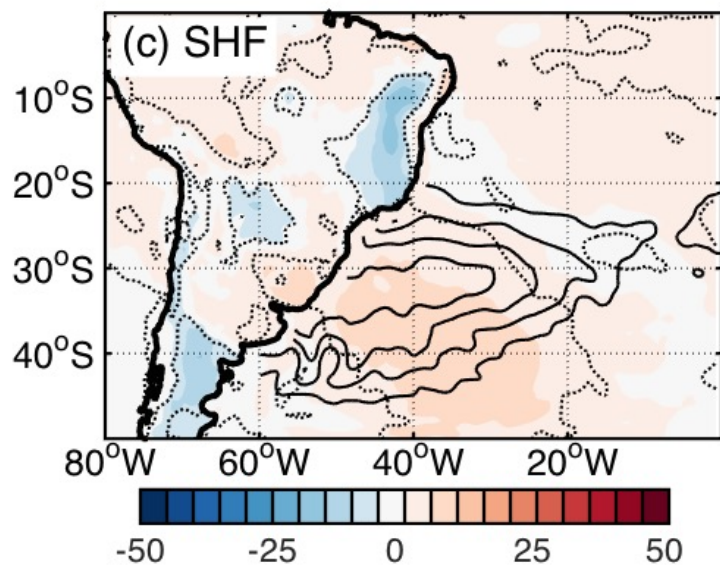
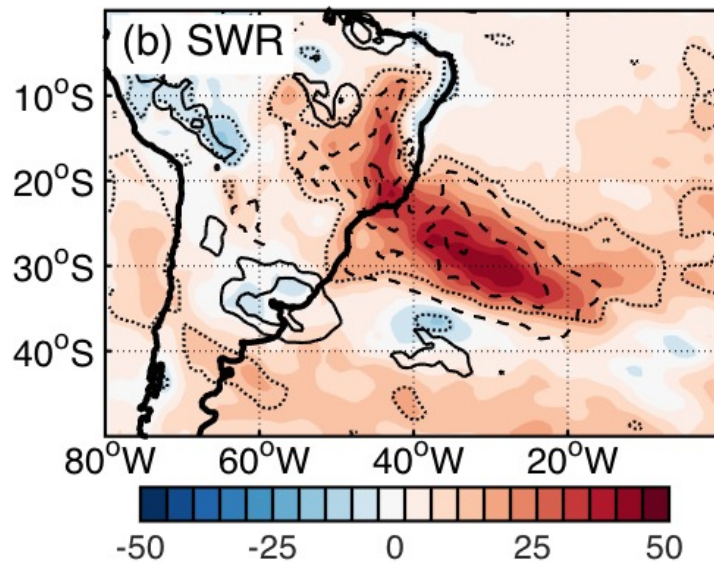
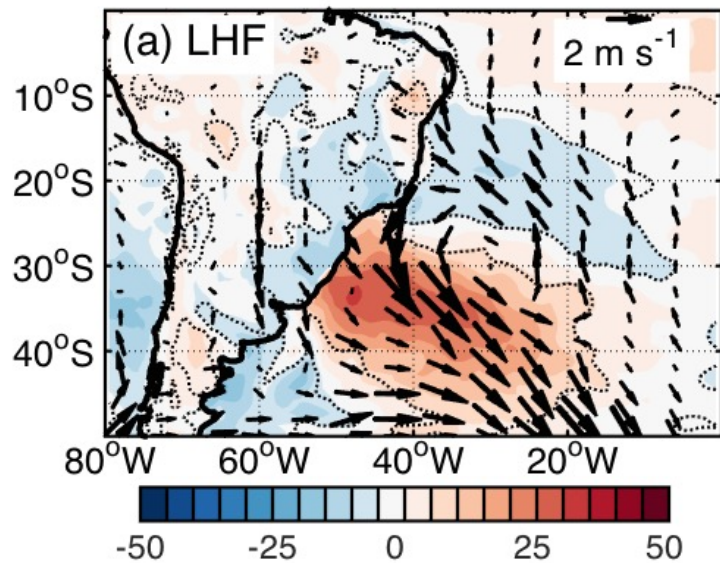
Marine Heatwaves in the Context of Compound Extremes

regina.rodrigues@ufsc.br 
@rrrocean 





Compound Events



Surface Heat Fluxes

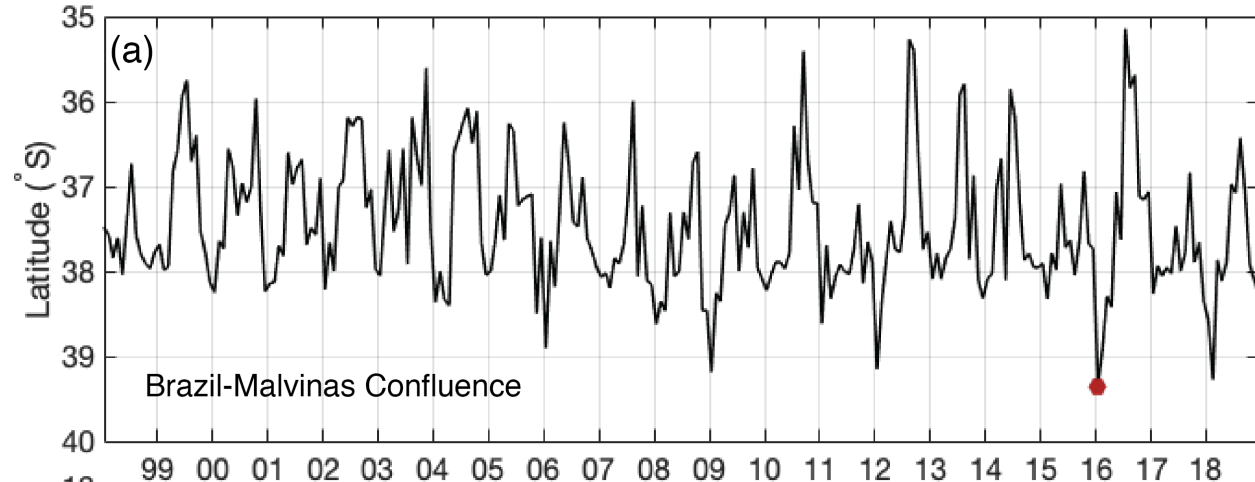
Rodrigues et al. (2019, Nat. Geo.)



Compound Events

Triple Compound: MHW + Low Chlorophyll + High Acidity

Confluence
Brazil-Malvinas



Angola Front

