Marine heatwaves and compound events: Attribution and future changes

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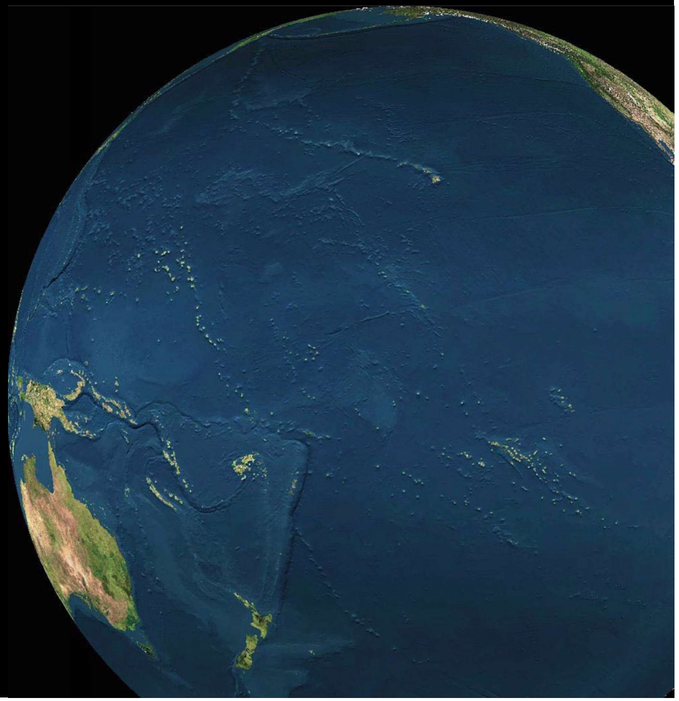
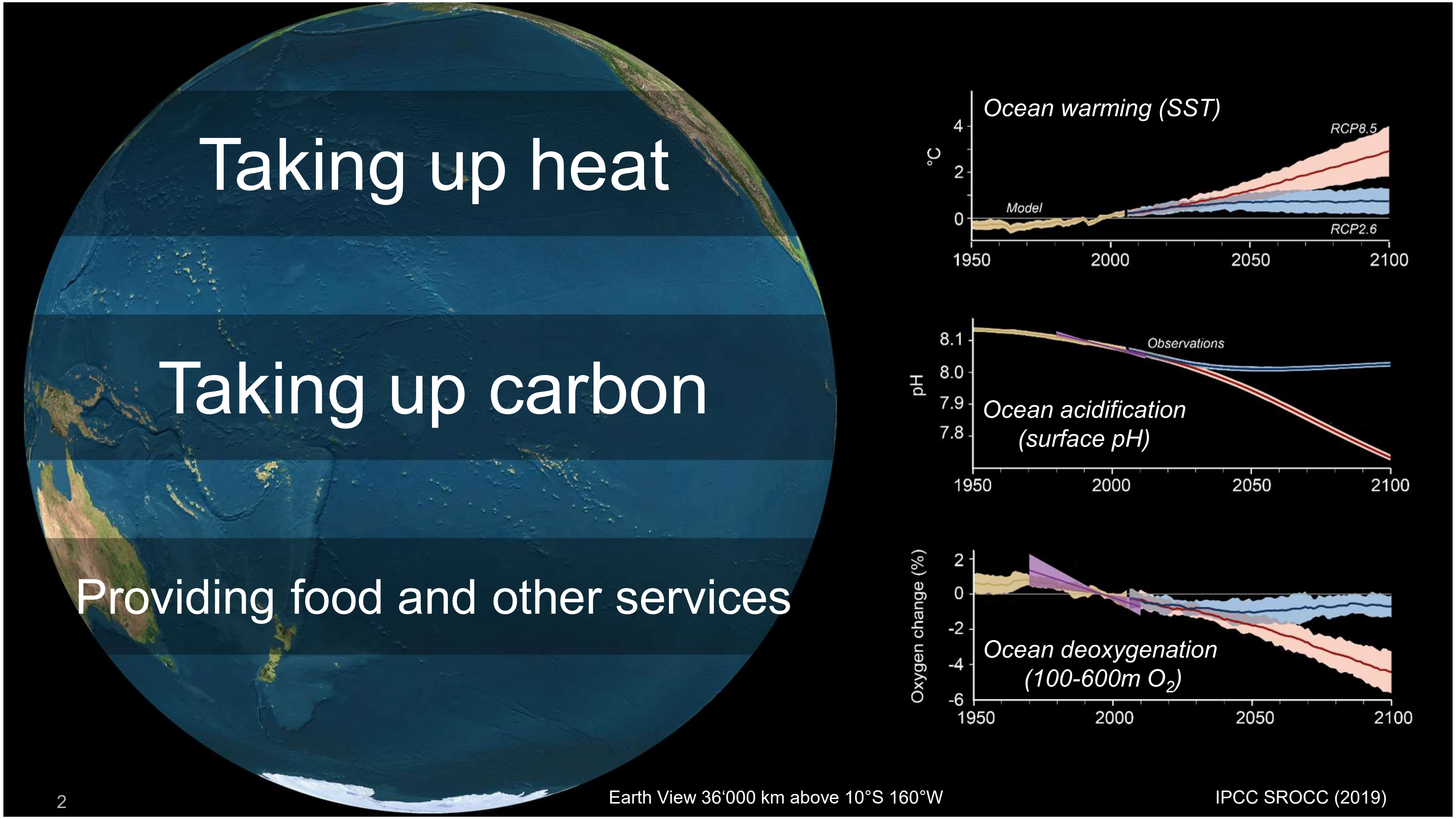
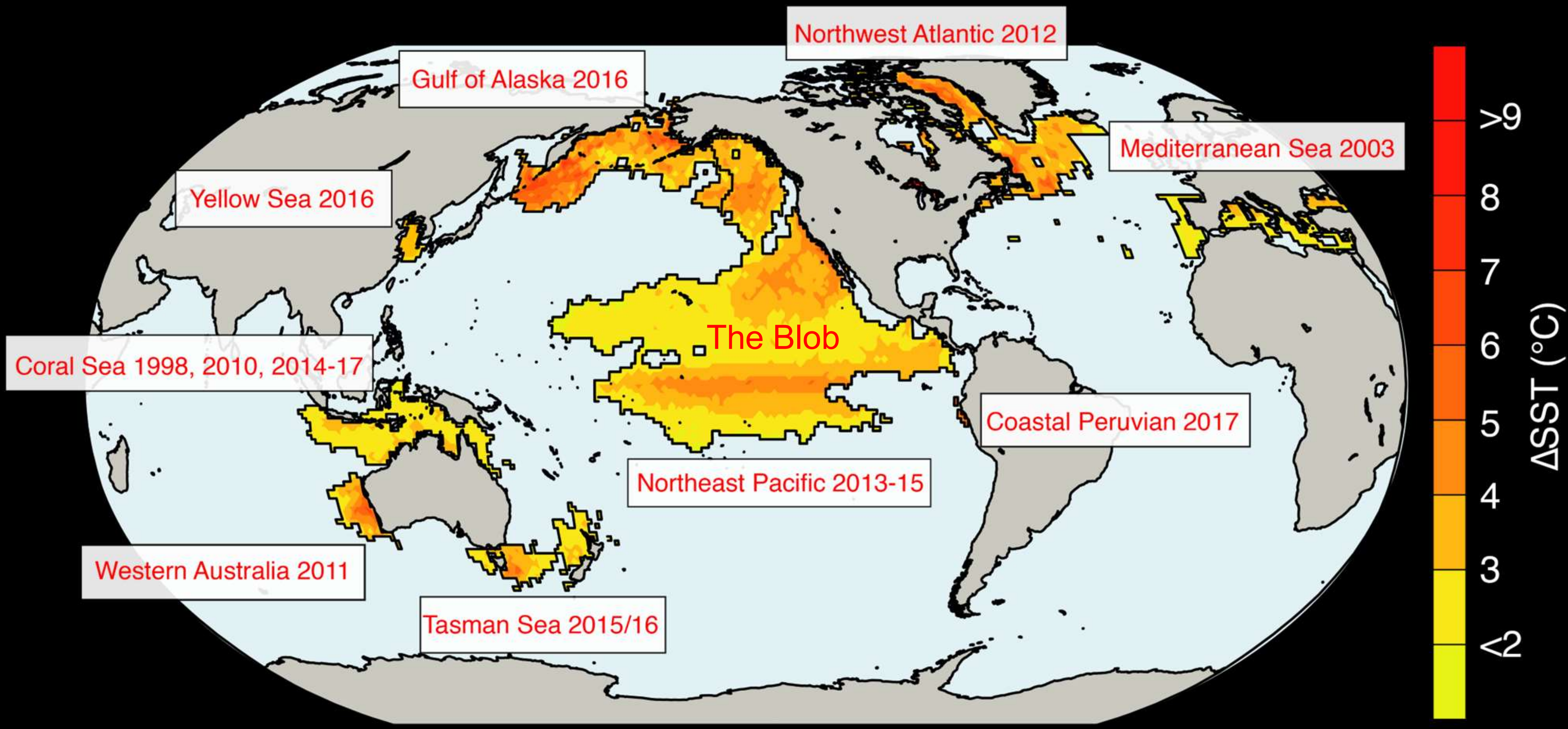


Swiss National Science Foundation
COMFORT
4C Climate-Carbon Interactions in the Current Century
AtlantECO
PROVIDE

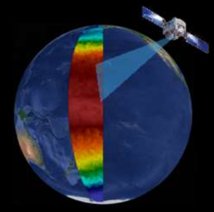

Taking up heat
Taking up carbon
Providing food and other services
Ocean warming (SST)
°C
4
2
0
Model
RCP8.5
RCP2.6
1950
2000
2050
2100
8.1
8.0
7.9
7.8
pH
Observations
Ocean acidification
(surface pH)
1950
2000
2050
2100
Oxygen change (%)
2
0
-2
-4
-6
Ocean deoxygenation
(100-600m O_2)
1950
2000
2050
2100
2
Earth View 36'000 km above 10°S 160°W
IPCC SROCC (2019)

Prominent marine heatwaves over the last two decades



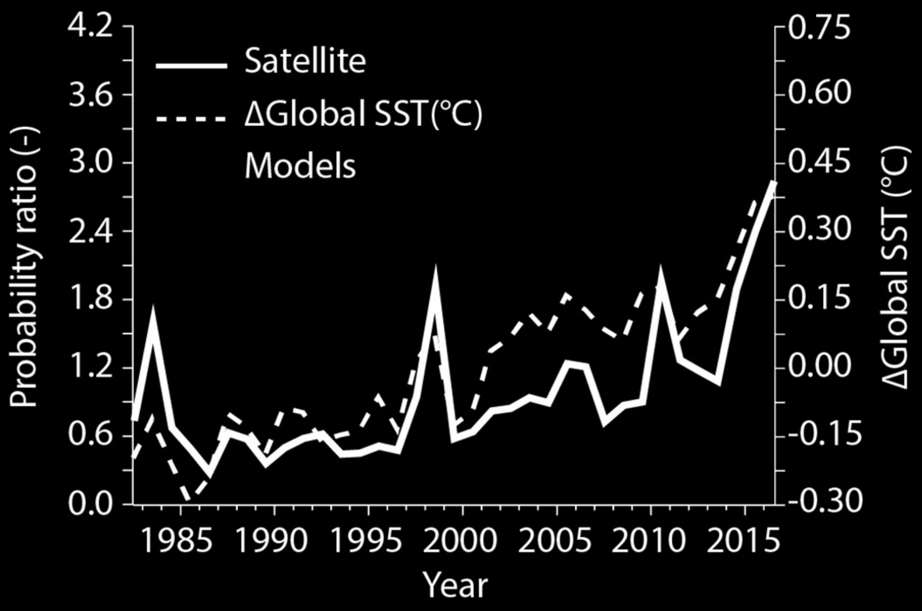
Frölicher and Laufkötter (2018, *Nature Communications*)

Marine heatwaves days have doubled over the satellite period



Definition MHW: 99 Percentile of 1982-2016 baseline period

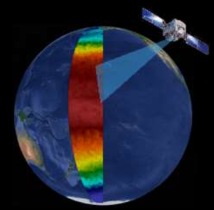
Probability ratio $= \frac{p(t)}{p(1982-2016)}$



- Global SST has increased by ~ 0.4°C
- The frequency of marine heatwaves has doubled between 1982 to 2016
- The duration, extent and intensity of marine heatwaves has also increased

Frölicher et al. (2018, *Nature*)

Trend is outside the range expected from internal variability



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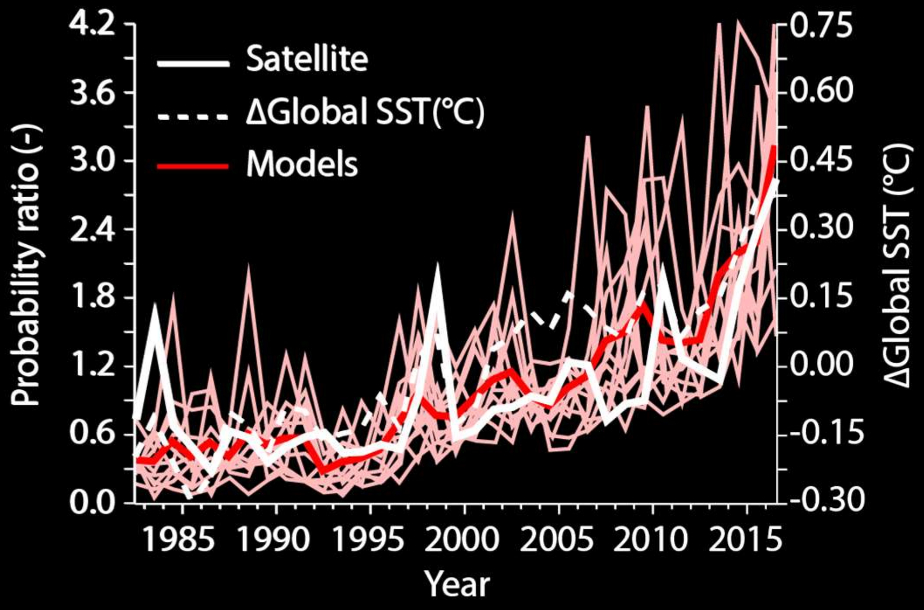
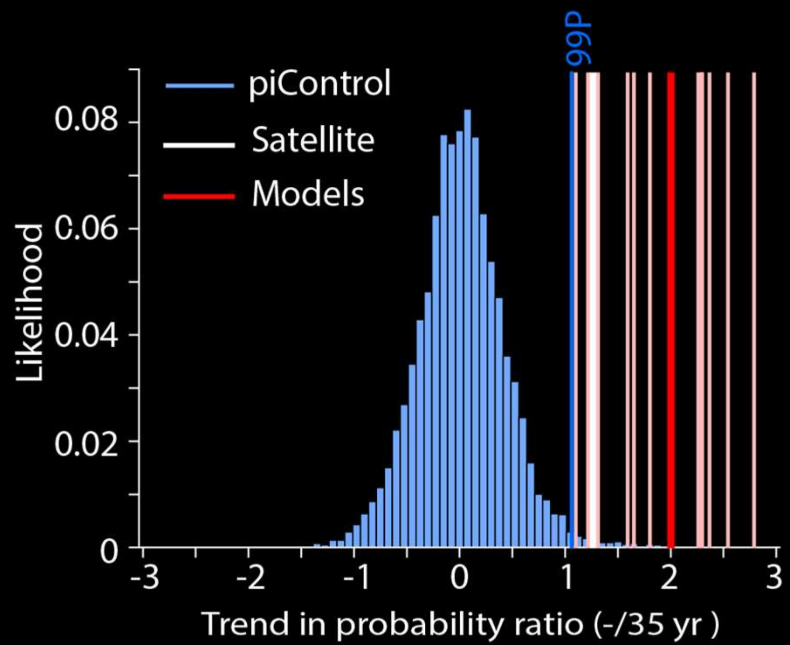
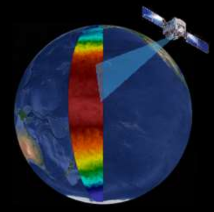
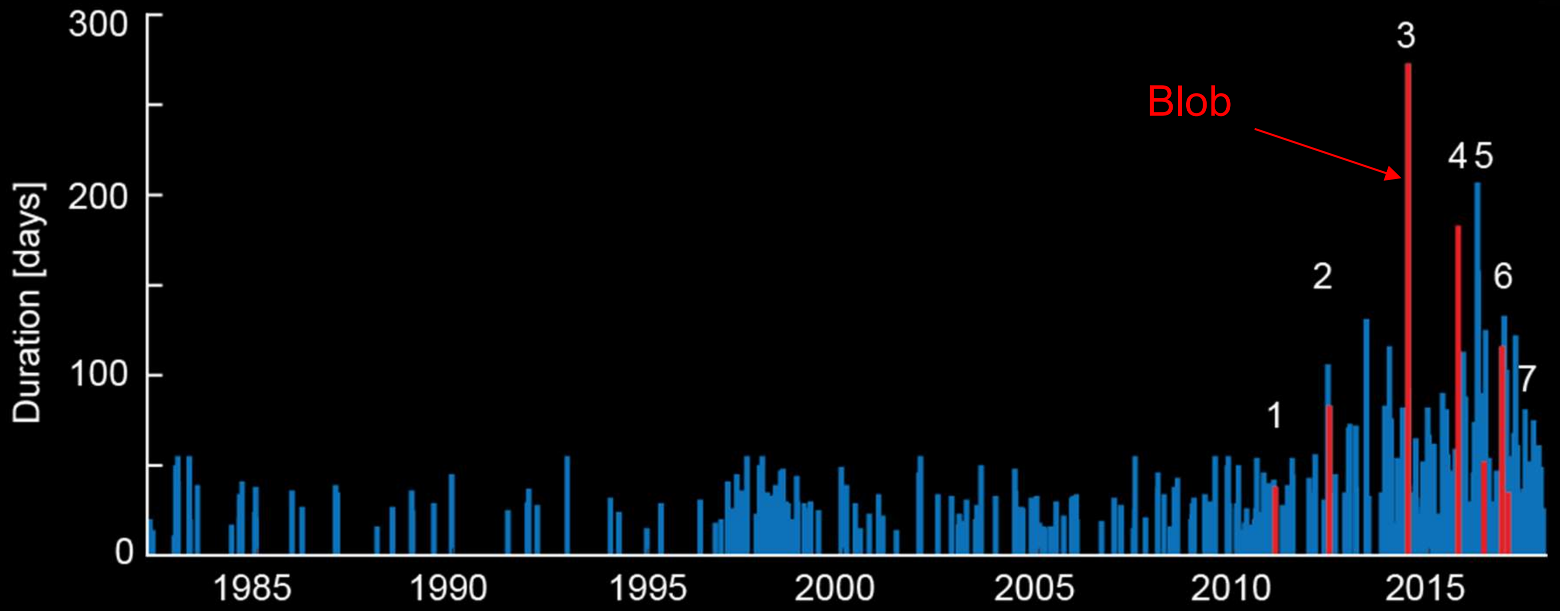




Marine heatwaves over the satellite period

Comparison of 300 largest marine heatwaves





- 1981-1990: 27 large MHWs; 32 days and 4.8°C
- 2008-2017: 172 large MHWs; 48 days and 5.5°C

Laufkötter et al. (2020, *Science)*

Outline

1. Past trends in marine heatwave frequency

    Q: have marine heatwaves changes over the historical period?

2. Attribution of marine heatwaves

    Q: has anthropogenic warming changed the odds of marine heatwaves?

3. Future changes in marine heatwaves

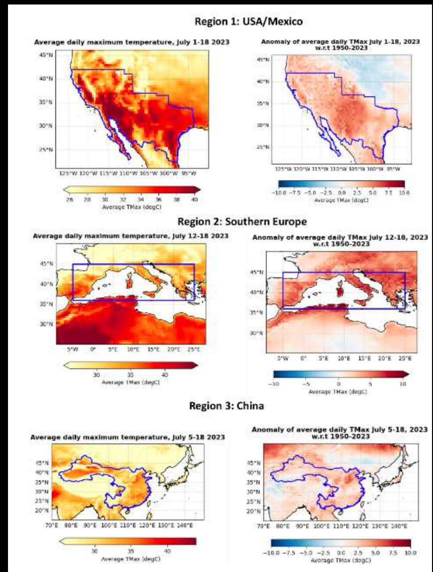
    Q: what can we expect in the future?

4. Future changes in ocean biogeochemical extremes and compound events

    Q: have we overlooked a potential serious problem?

Extreme event attribution is a rapidly growing field

- *10 years ago: ‘no individual extreme event can be attributed to climate change’*
- *Today: ‘we can calculate the influence of climate change on some types of specific extreme events’*
- Near-real time attribution of events by World Weather Attribution



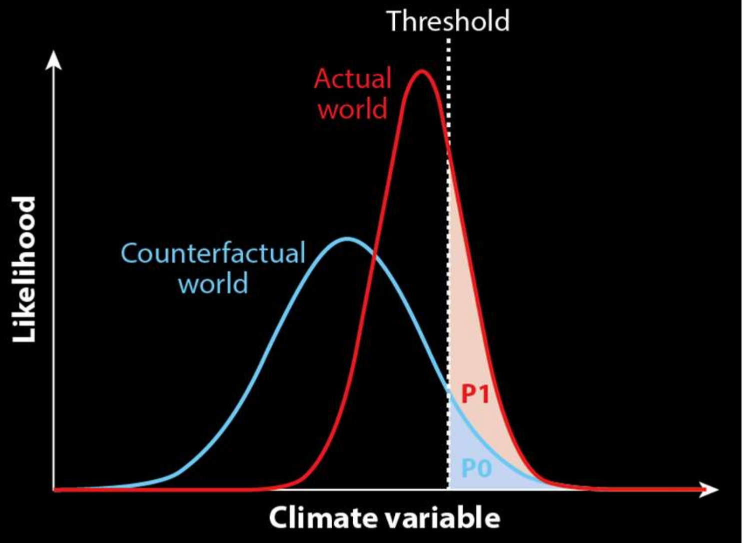
https://www.worldweatherattribution.org

Different methods exist

There are many methodologies for extreme event attribution analysis. First method was pioneered in 2003/2004 by Allen (2003) and Stott et al. (2004)

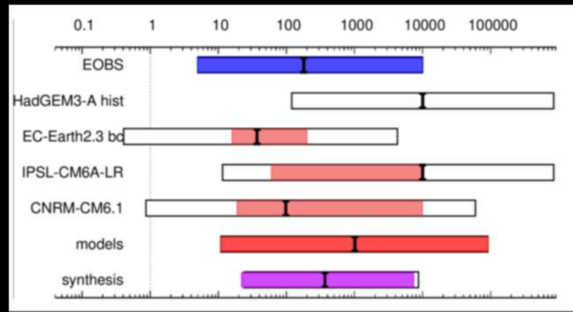
1. Probability-based approach

- Probability of the event in the present-day climate, p_1
- Probability of the event in past climate/counterfactual climate without anthropogenic influences, p_0
- Probability ratio: PR = p_1/p_0
- Fraction of Attributable Risk: FAR = $1- p_0/p_1$



2. Storyline approach (e.g., Shepherd 2016)

Probability-based approach:
Eight step procedure (Philip et al. 2020, Oldenborgh et al. 2021)



Step 1: Analysis trigger: which events do we attribute?

Step 2: Event definition: how do we define the event quantitatively?

Step 3: Observed probability and trend

Step 4: Model evaluation

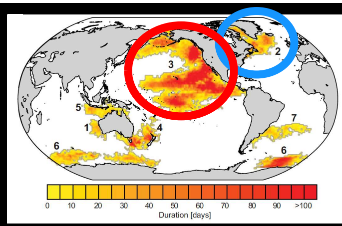
Step 5: Multi-method multi-model attribution (step originally proposed by Allen 2003)

Step 6: Hazard synthesis: synthesis of different results into a single attribution statement

Step 7: Vulnerability and exposure analysis: Risk depends on hazard, exposure and vulnerability

Step 8: Communication: likelihood increased, decreased, not changed, unable to determine

Most impactful heatwaves became more than 20-fold more likely due to human-induced global warming



Heatwave number	Time and location	Intensity (°C)	FAR intensity	Duration (days)	FAR duration
1	Western Australian 2011	2.26	–	101	0.79 [−0.55, 0.97]
2	Northwest Atlantic 2012	2.15	0.97 [0.92, 0.99]	57	0.96 [0.94, 0.97]
3	Northeast Pacific 2013 to 2015	1.56	1.0 [0.97, 1.0]	357	1.0 [0.99, 10]
4	Tasman Sea 2015 and 2016	1.49	0.98 [0.92, 0.99]	175	1.0 [0.49, 1.0]
5	Indo-Australian Basin 2016	1.67	1.0 [0.77, 1.0]	90	–
6	Southern Ocean 2016*	1.0	0.03 [−2.71, 0.74]	183	−0.6 [−2.6, 0.26]
7	Southwest Atlantic 2017	1.96	1.0 [0.74, 1.0]	82	1.0 [0.91, 1.0]

Northwest Atlantic 2012 marine heatwave

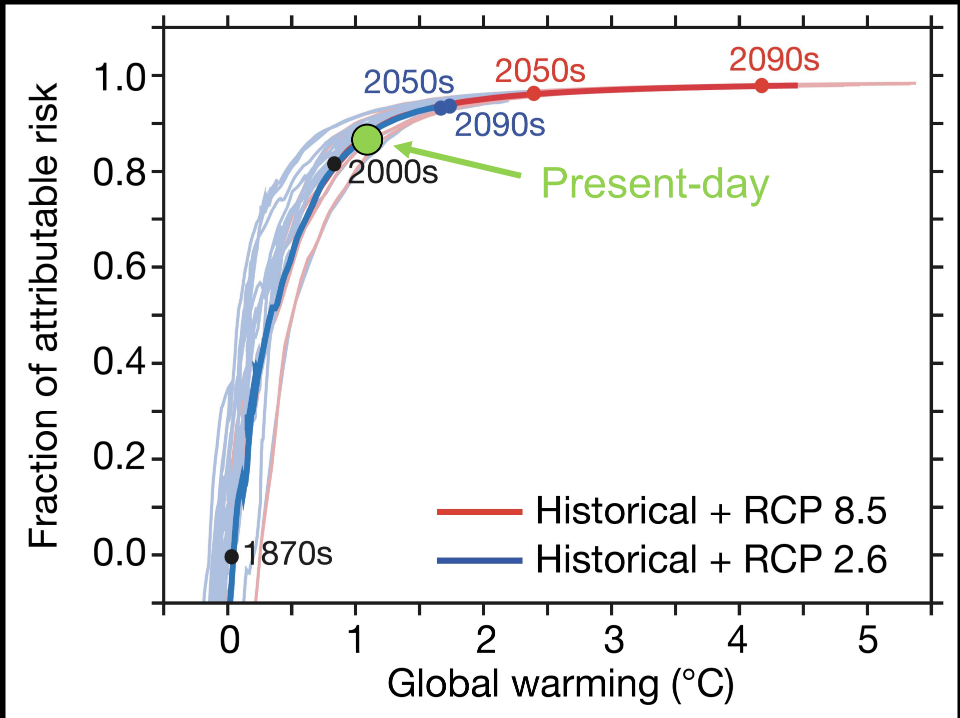
- 2.15°C → 33x more likely by 1982-2017 than preindustrial
- 57 days → 25x more likely by 1982-2017 than preindustrial

Northeast Pacific 2013-2015 marine heatwave ('Blob')

- 1.56°C → only possible due to climate change
- 357 days → only possible due to climate change

Laufkötter et al. (2020, *Science*)

Most of today's marine heatwaves are attributable to global warming



It is very likely that between 84-90% of marine heatwaves that occurred between 2006 and 2015 are attributable to the anthropogenic temperature increase

Frölicher et al. (2018, *Nature*)

Not all types of extreme weather events are attributable with confidence

high confidence: e.g., heat and cold events

low confidence: e.g., tornadoes, wildfires, hail

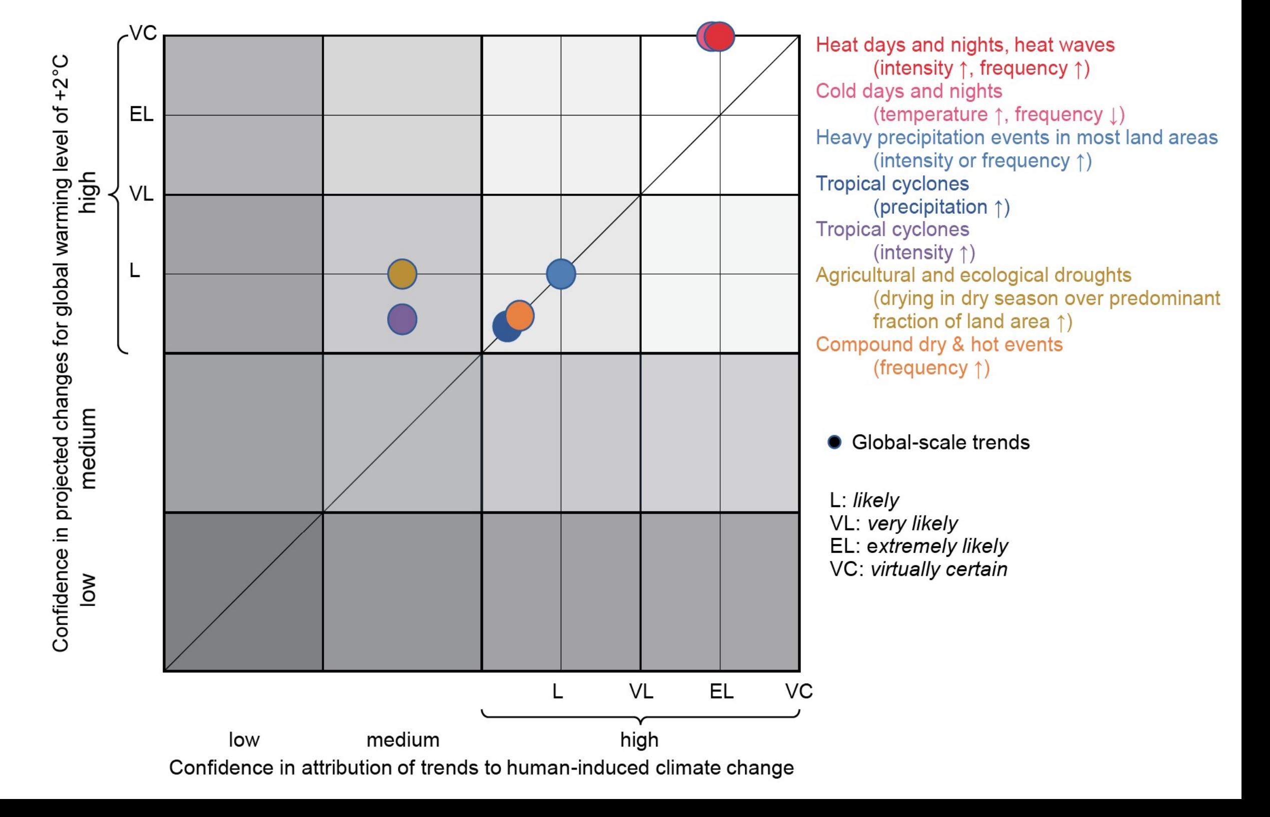


Fig. 11.5; IPCC AR6 WGI Chapter 11

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The effect of changes in temperature distribution on extremes

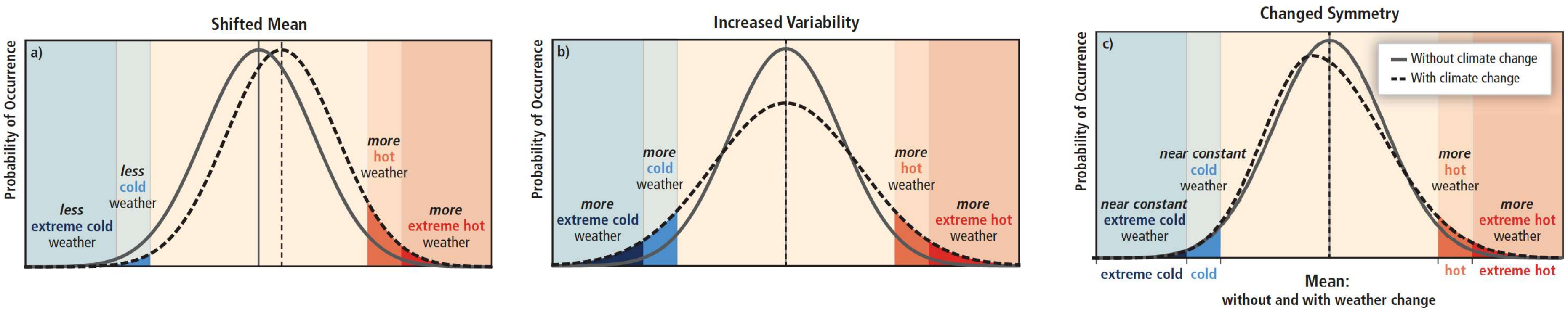
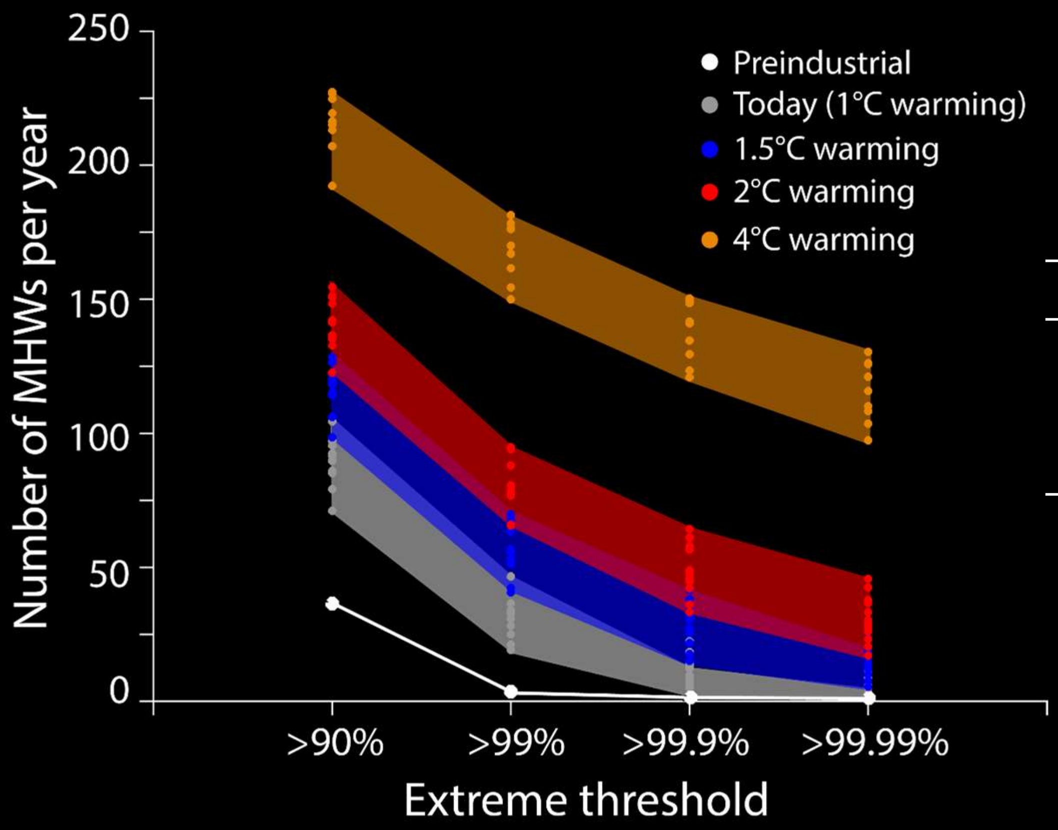


Fig SPM.3, IPCC SREX

Simulated changes in number of marine heatwave days per year

Definition MHW: 99 Percentile of piControl



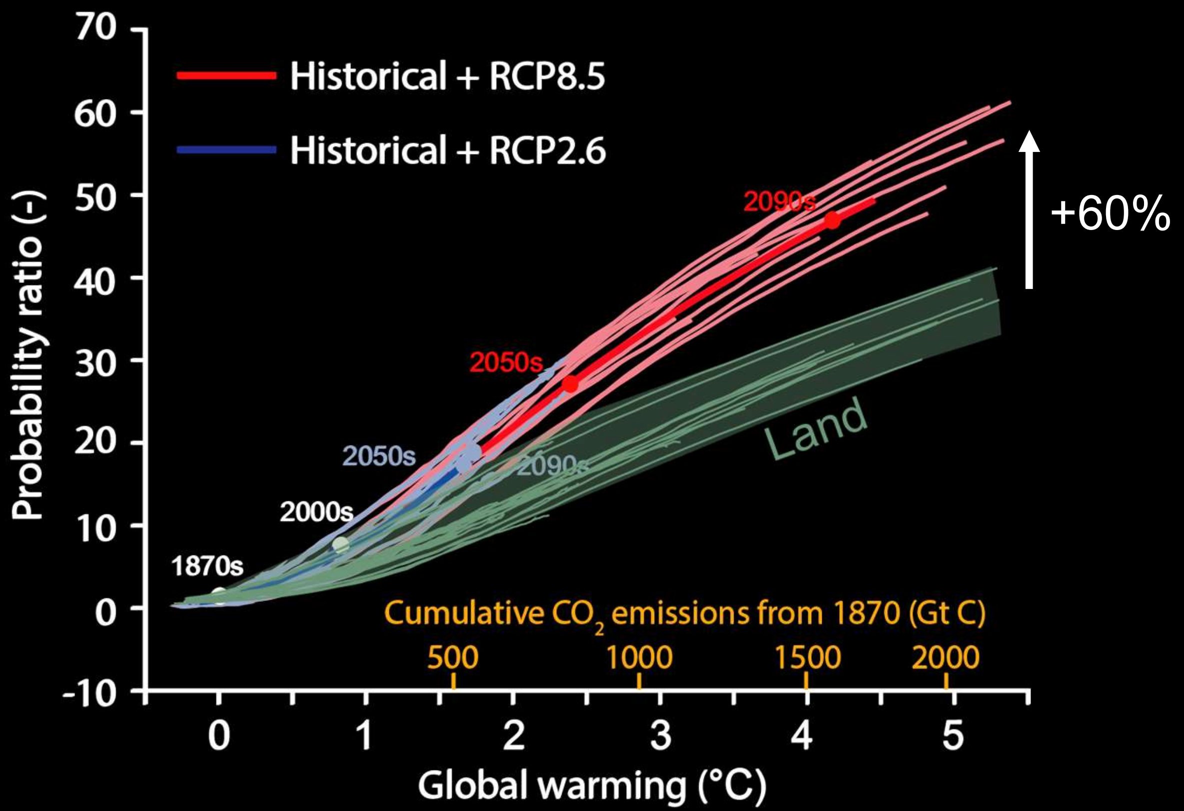
	>99%	>99.99%
Preindustrial	1 in 100 day	1 in 27 year
1°C warming	1 in 11 day	1 in 71 day
3.5°C warming	1 in 2 day	1 in 4 day

Frölicher et al. (2018, *Nature*)

Strong increase in marine heatwave frequency with further global warming

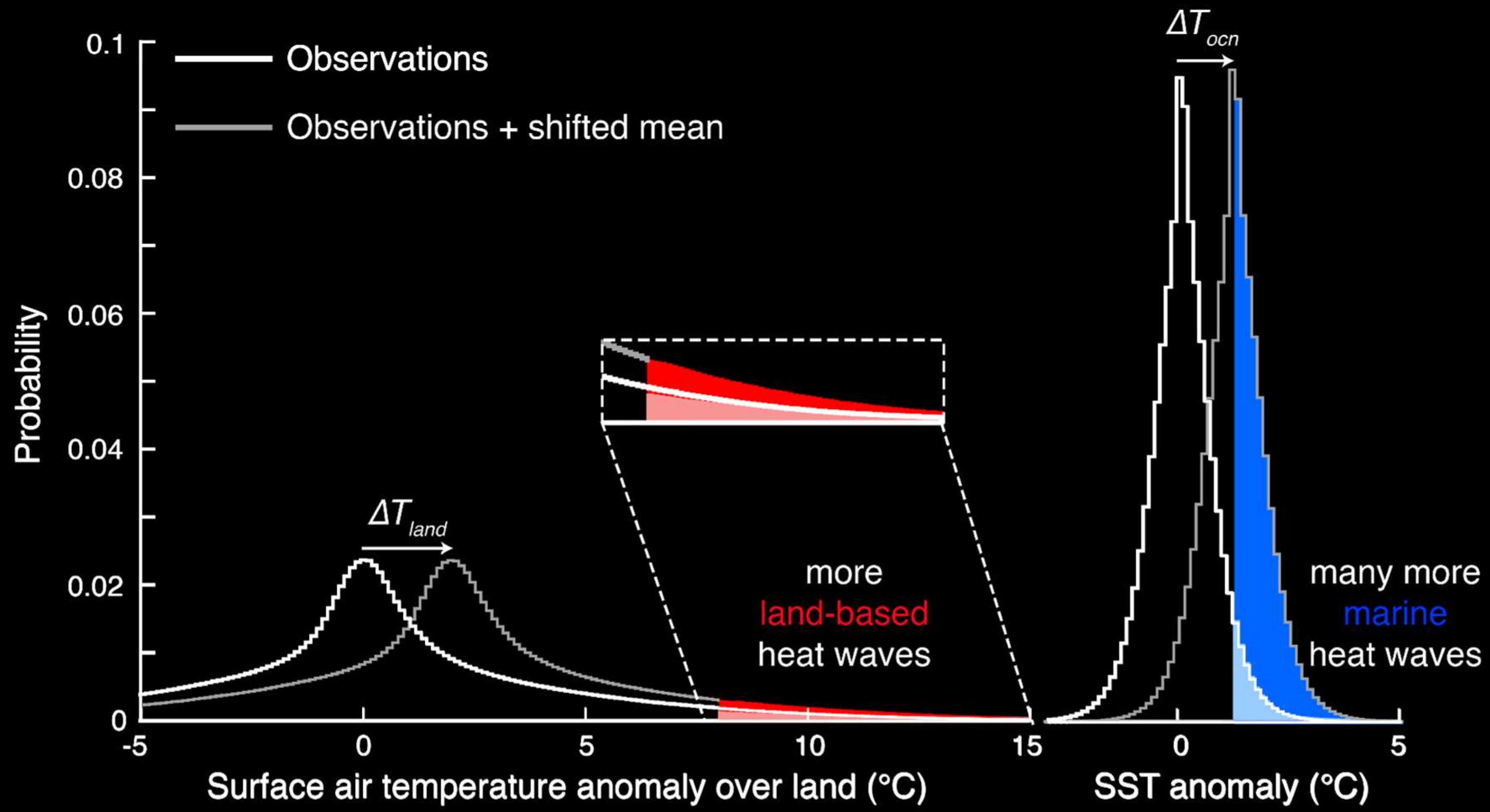
Definition MHW: 99 Percentile of piControl

$$\text{Probability ratio} = \frac{P_1}{P_0}$$



Frölicher et al. (2018, *Nature*)

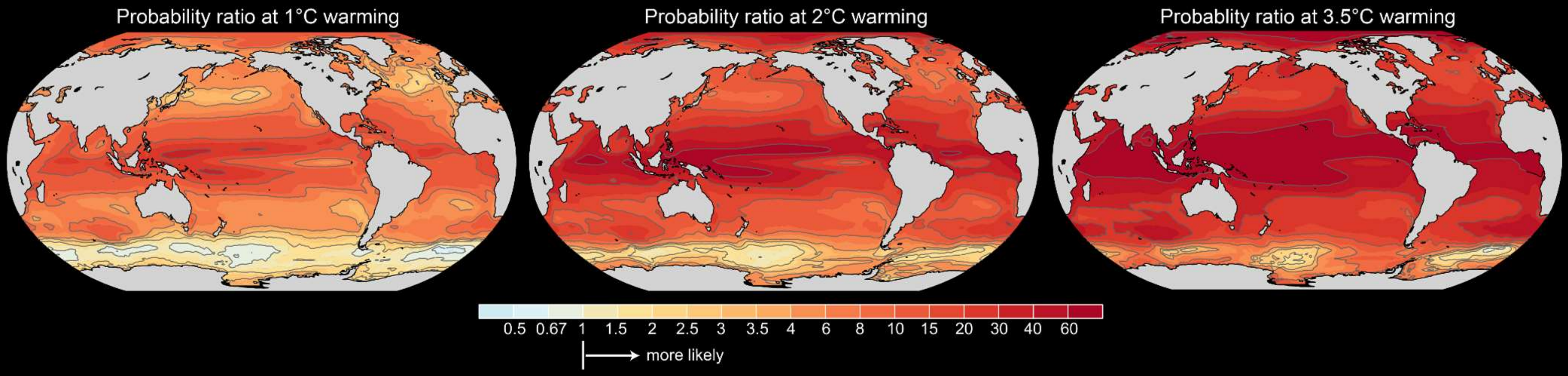
Marine heatwaves versus terrestrial heatwaves



Frölicher and Laufkötter (2018, *Nature Communications*)

Largest increase in probability of MHWs in tropical and Arctic Ocean

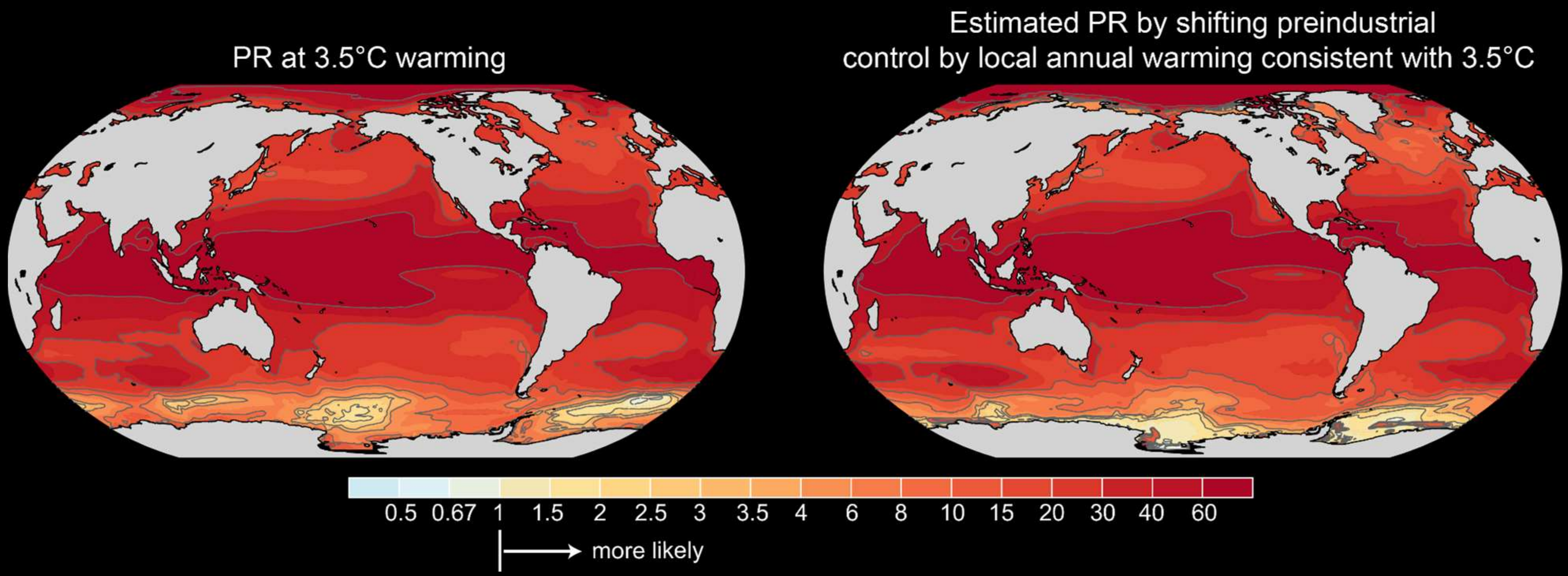
Definition MHW: 99 Percentile of piControl



- Largest increase in MHW frequency in Arctic and tropical ocean. Small changes in Southern Ocean.

Frölicher et al. (2018, *Nature*)

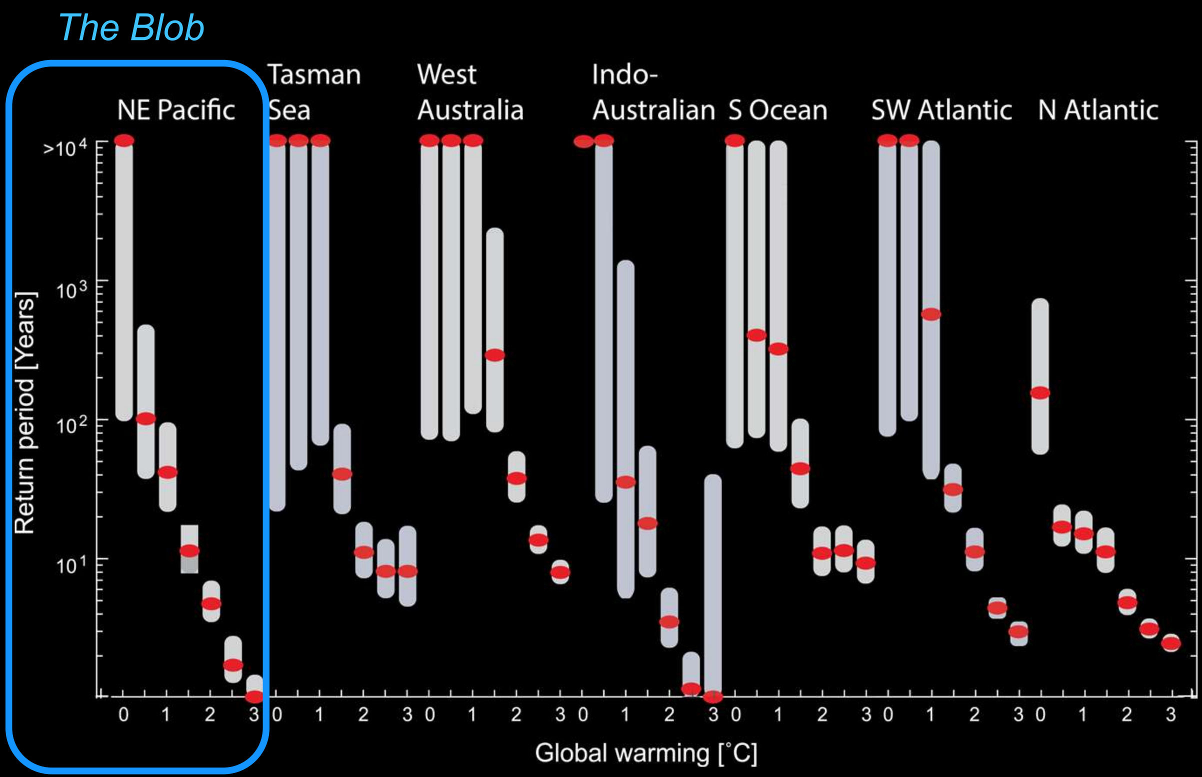
Changes in MHW frequency can be explained by global ocean warming

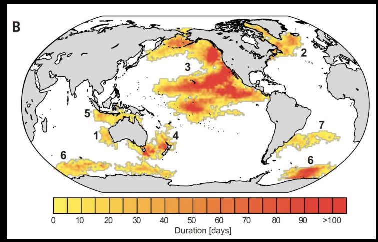


→ See also talk by Clara Deser

Frölicher et al. (2018, *Nature*)

Many rare marine heatwave events will become decadal to annual events

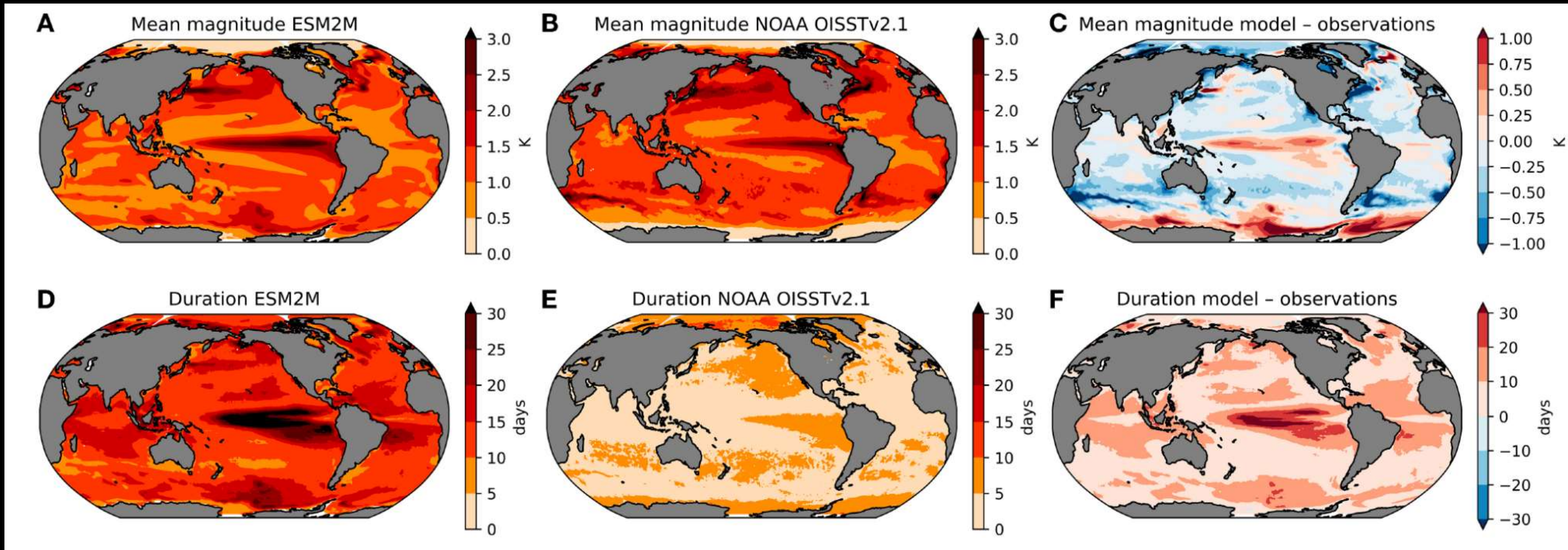




Marine heatwaves that typically occurred once in hundreds to thousands of years in preindustrial times, likely occur on an annual to decadal basis if global temperature rises by 3°C

Laufkötter et al. (2020, *Science*)

Are CMIP-type Earth system models fit for purpose?



Vogt et al. (2022; Frontiers) See also Pilo et al. (2019; *GRL*), Hayashide et al. (2020; *Nature Communications*)

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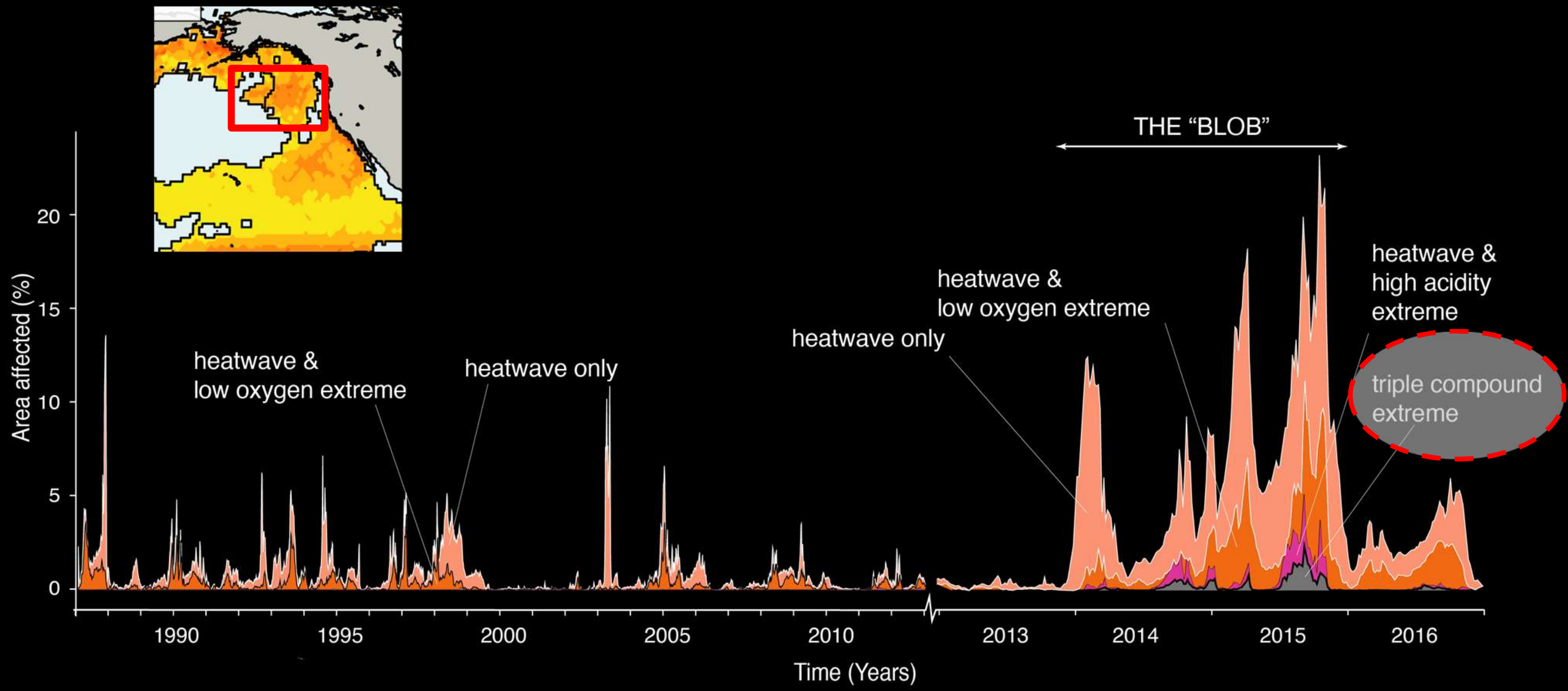
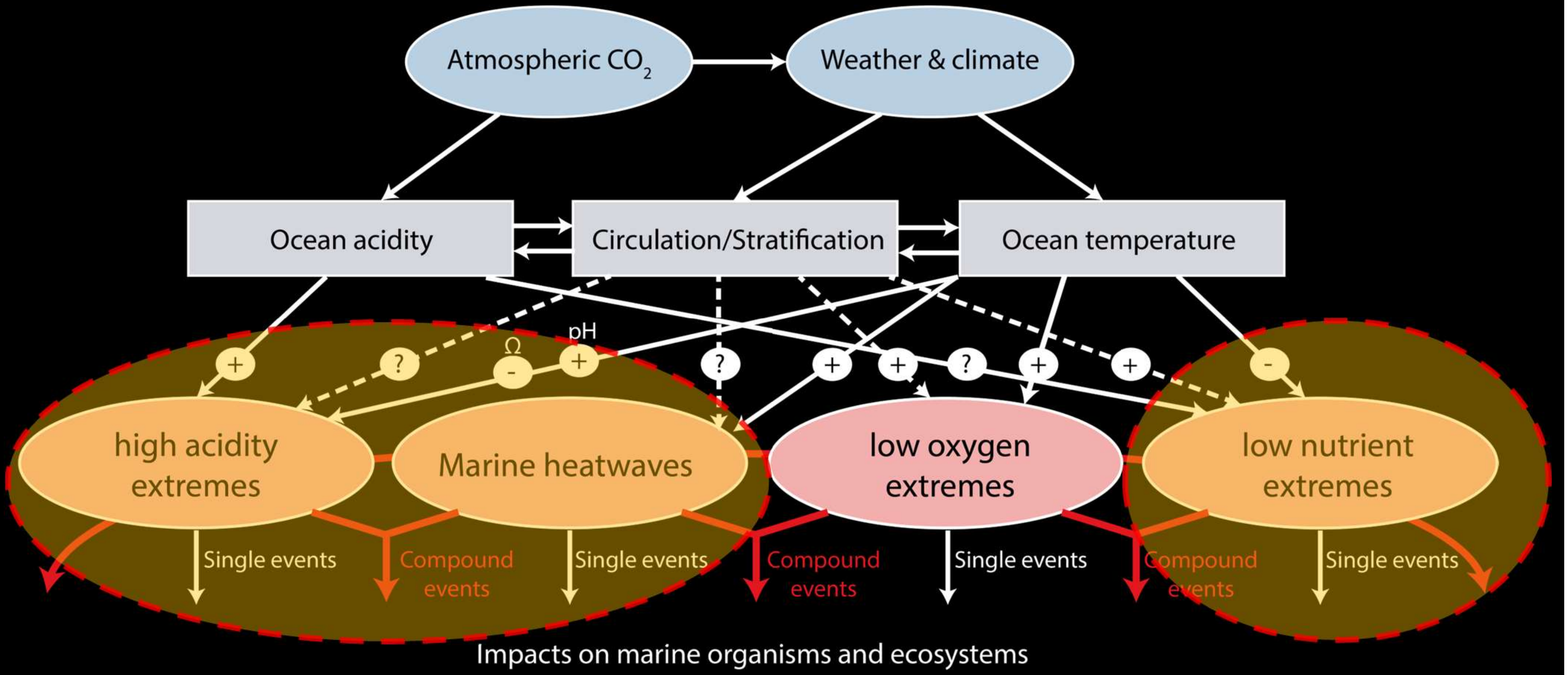
Compound events in the ocean are a new phenomena



Gruber et al. (2021, *Nature*)

From marine heatwaves to compound events

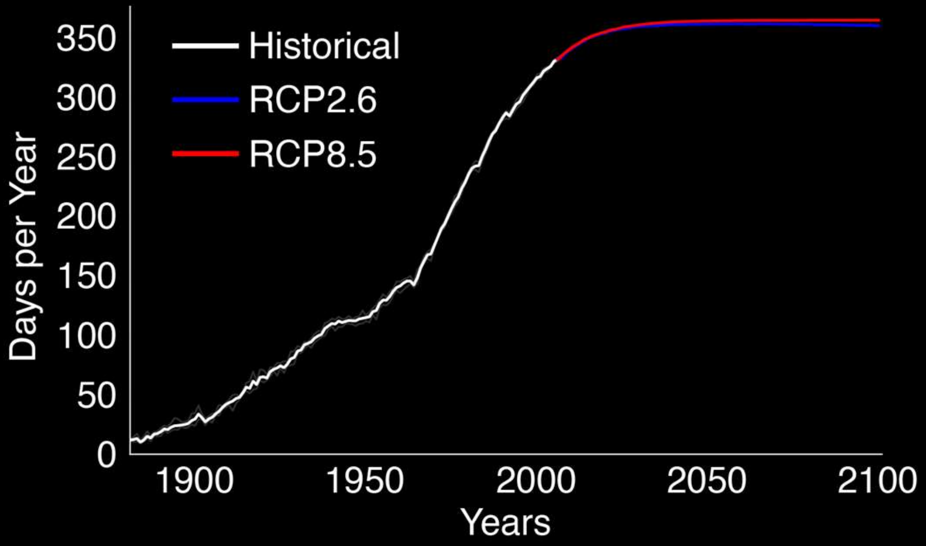


modified from Gruber et al. (2021 *Nature*)

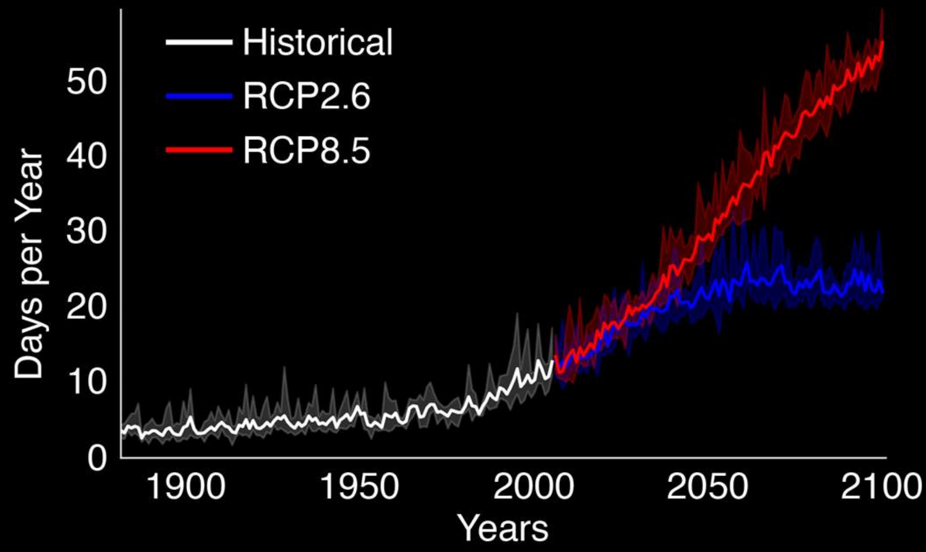
Large increase in the number of surface ocean acidity ([H^+]) extreme days

Results from GFDL ESM2M-LE; Definition [H^+] extreme: 99 Percentile

Total changes
(fixed preindustrial baseline)



Variability-driven changes
(shifting baseline)

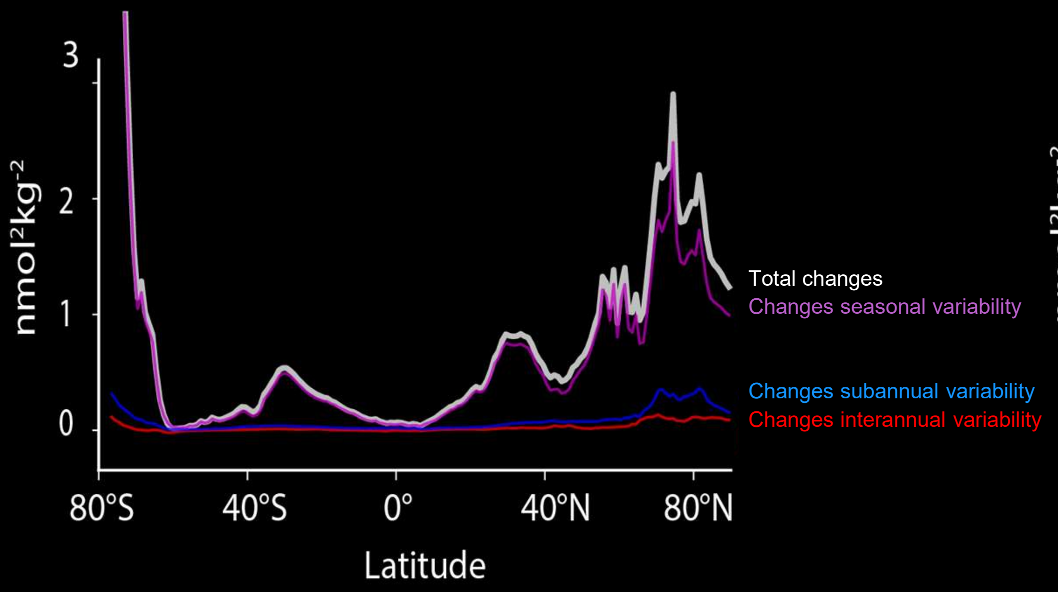


Note : The number of variability-driven extreme events days in Ω_{arag} decreases!

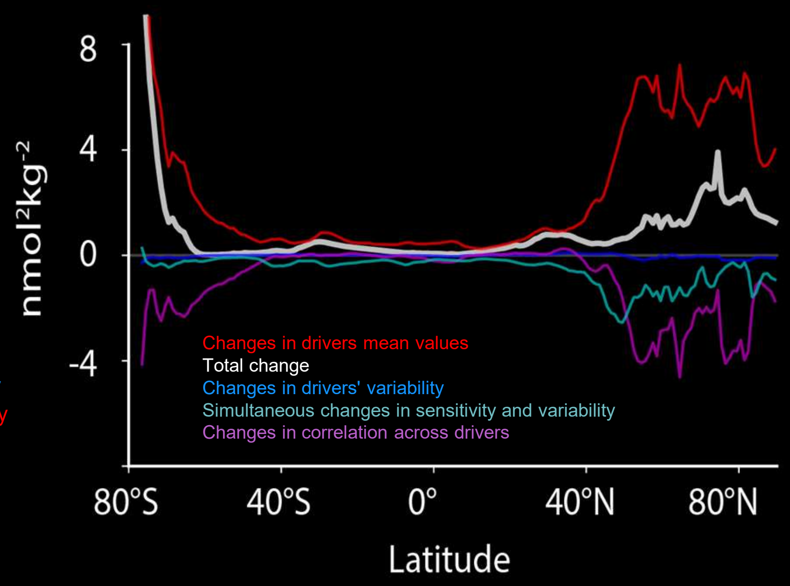
Burger, John, Frölicher (2020, *Biogeosciences*)

Decomposition and drivers of [H⁺] variability changes: 2090s – 1870s

Contribution to projected changes in [H⁺] variance



Drivers of [H⁺] variability change
(DIC, Alkalinity, Temperature, Salinity)

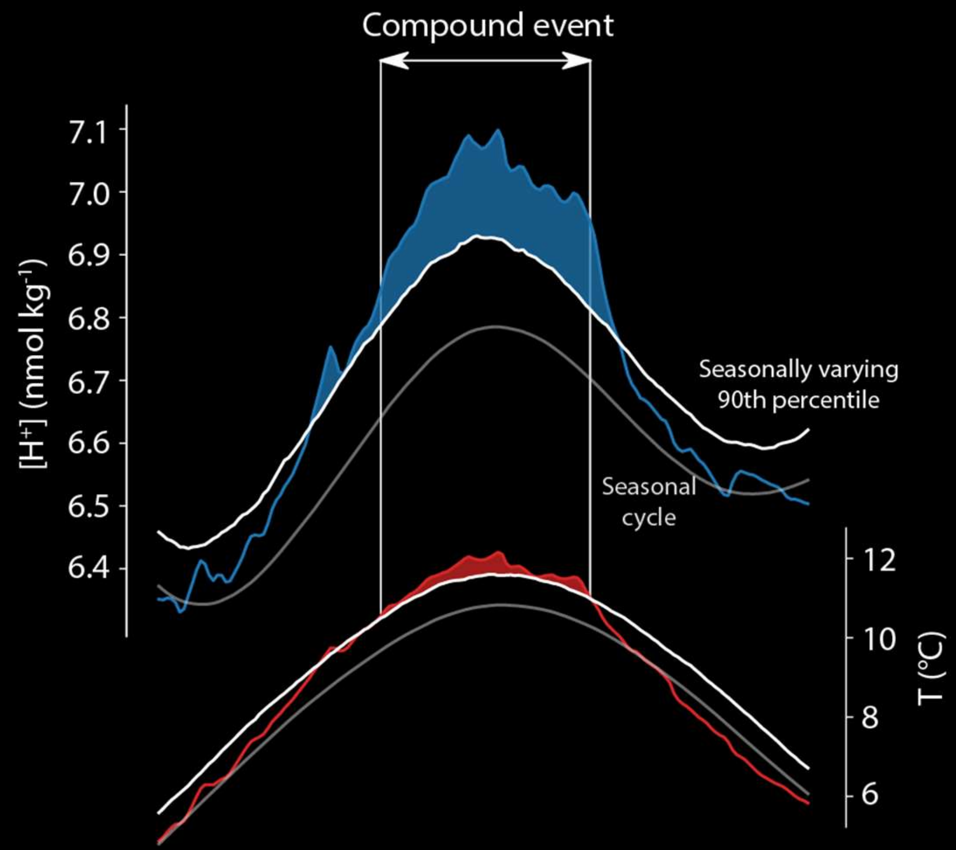


- Surface [H⁺] extremes will become more frequent in 87% of the ocean
- Largest increase in the Arctic Ocean and subtropical gyres
- Most of the variance increase is due to increase in [H⁺] seasonality

- Raise in variance is mainly driven by increase in mean surface DIC and decrease in mean alkalinity, somewhat damped by reduction in DIC variability

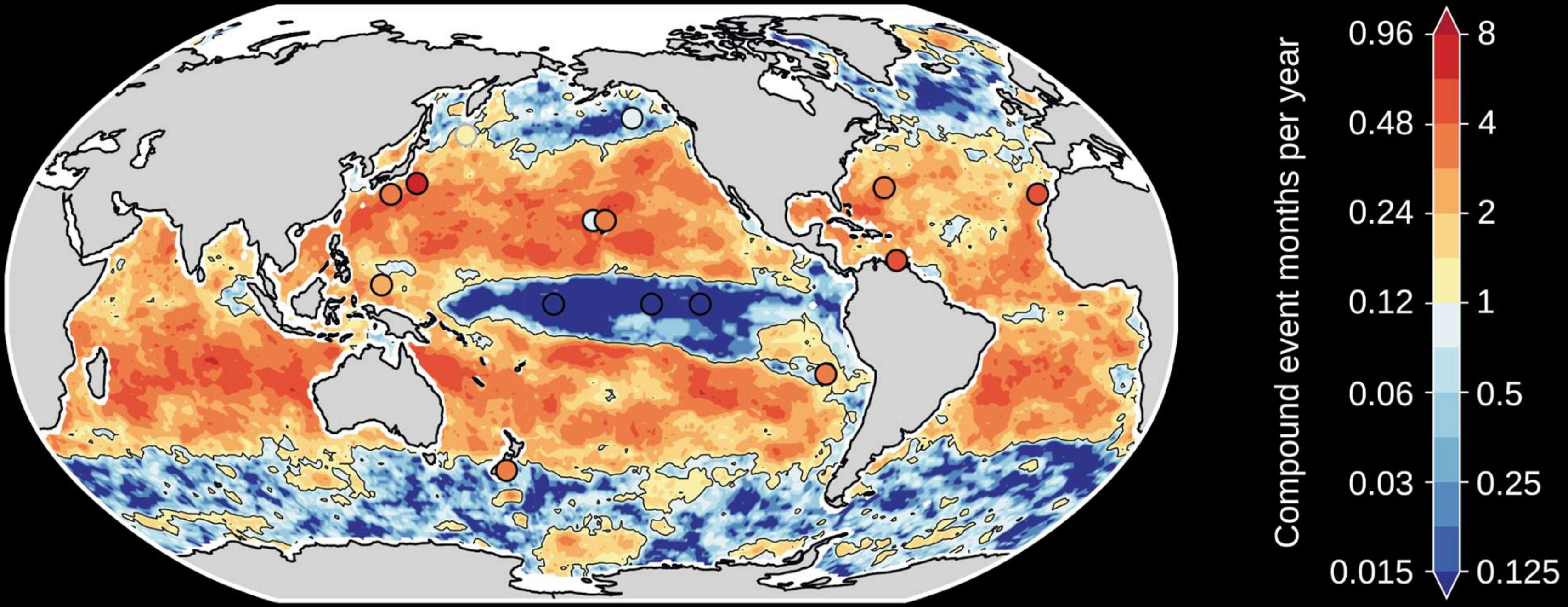
Burger et al. (2020, *Biogeosciences*)

Definition of multivariate compound events



- Combination of multiple drivers and/or hazards that contribute to societal or environmental risk (e.g., Zscheischler et al. 2018)
- Situations when more than one ocean ecosystem driver is outside the norm simultaneously (in my analysis), in close spatial proximity or temporal succession

Hotspots of compound marine heatwave - high acidity extremes

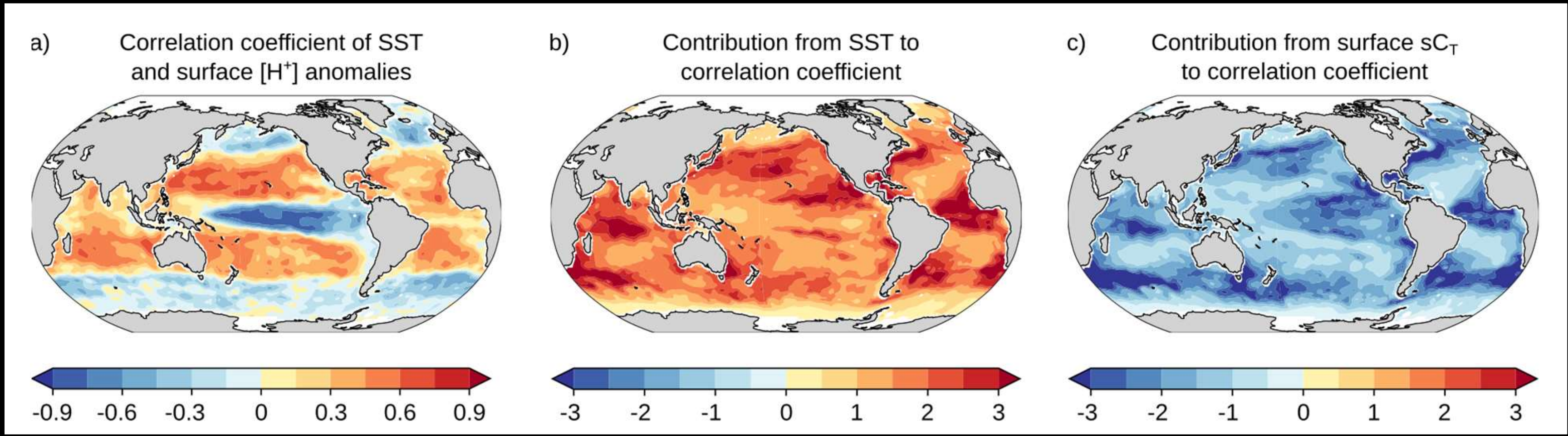


Circles: Estimates from 15 stations with time-series observations

Monthly gridded [H^+] data for 1982-2019: T, S from EN4.2.1 (Good et al. 2013); pCO_2 from MPI-SOM-FFN (Landschützer et al. 2020), A_T from LIARv2 regression (Carter et al. 2017)

Burger et al. (2022, *Nature Communications*)

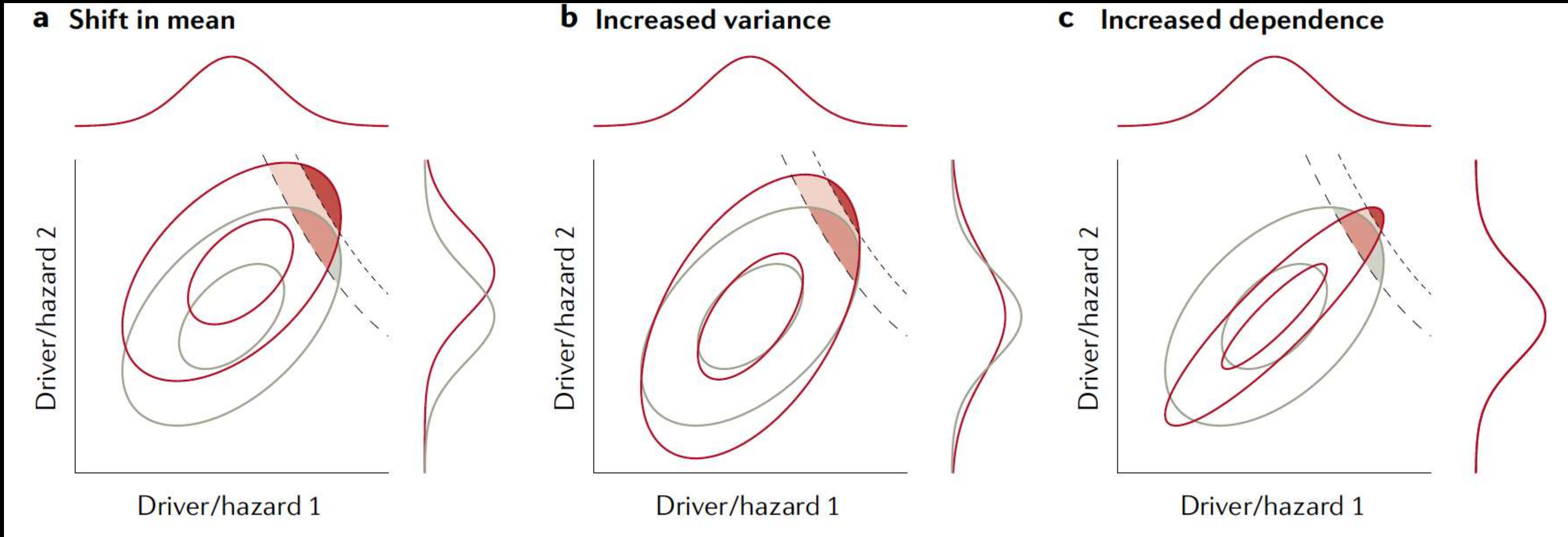
Drivers of compound marine heatwave-ocean acidity events



- Correlation coefficient is the net of the positive temperature contribution (increasing SST-$[H^+]$ correlation) and the negative sC_T contribution

Burger et al. (2022, *Nature Communications*)

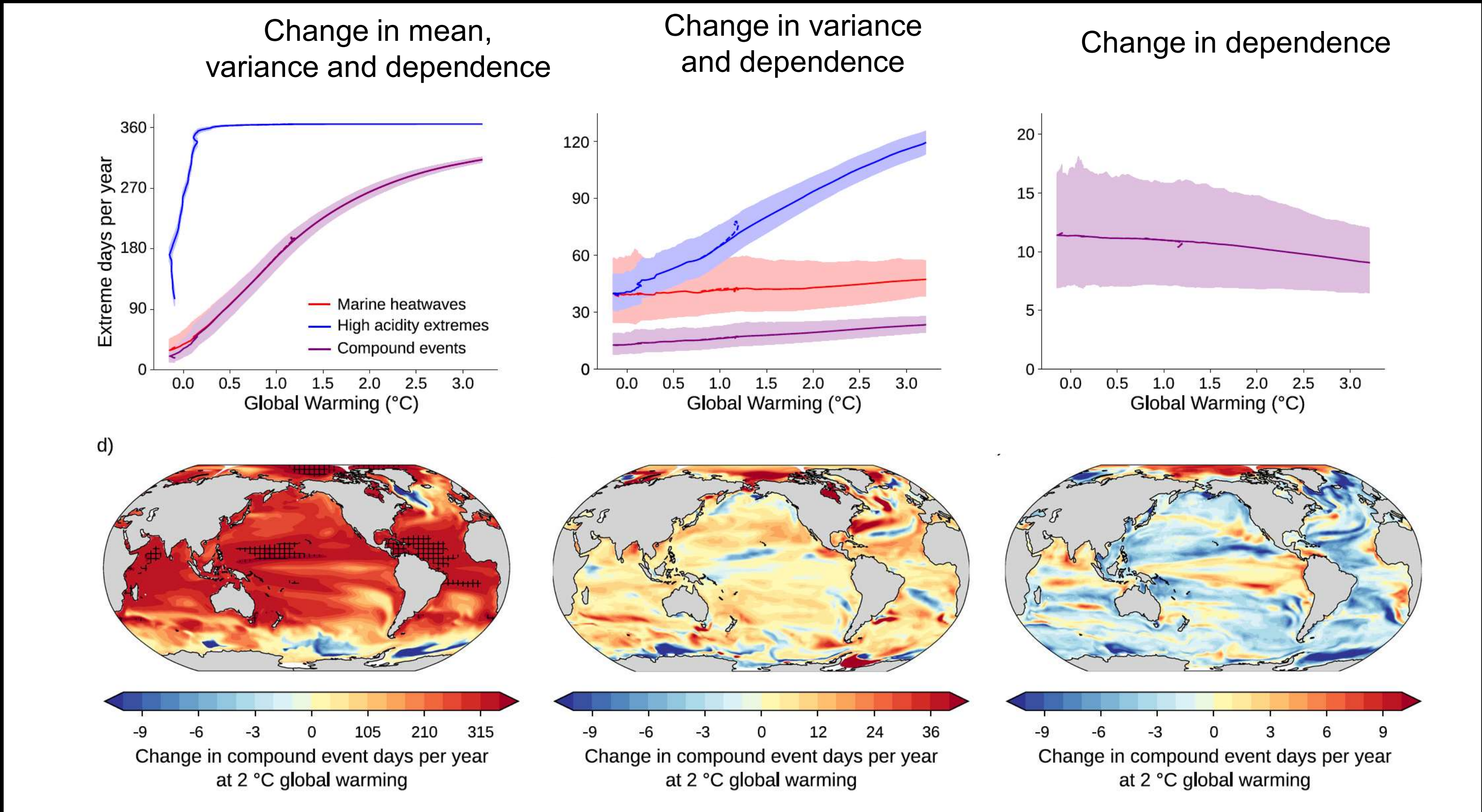
Climate change effects on compound events



Zscheischler et al. (2020, *Nature Reviews Earth & Environment*)

GFDL ESM2M-LE: MHW-OAX frequency under global warming

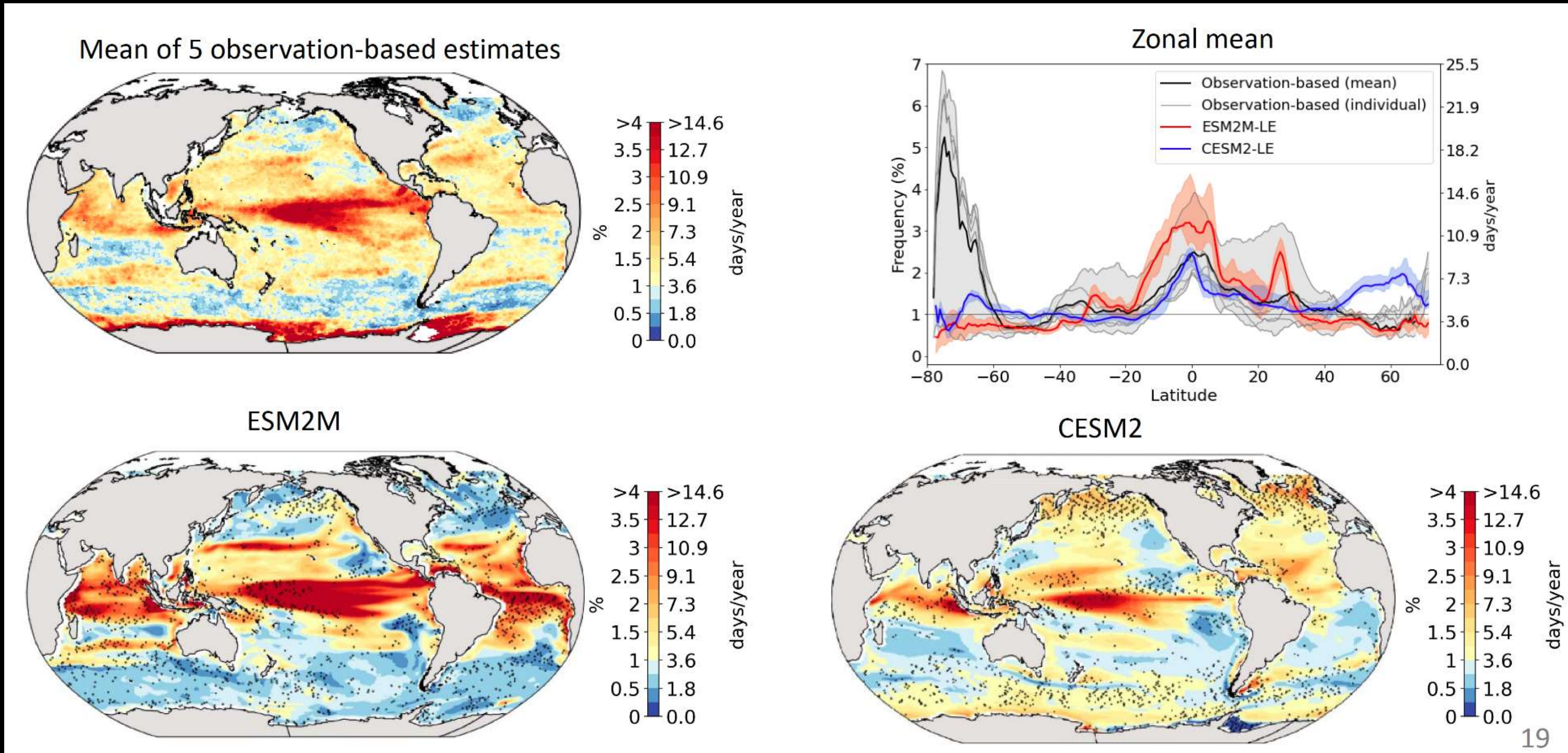
Results from daily data of a 30-member ensemble simulation with GFDL ESM2M; Definition extreme: 90 Percentile



Burger et al. (2022, *Nature Communications*)

Hotspots of compound marine heatwave-low NPP events

1998-2018

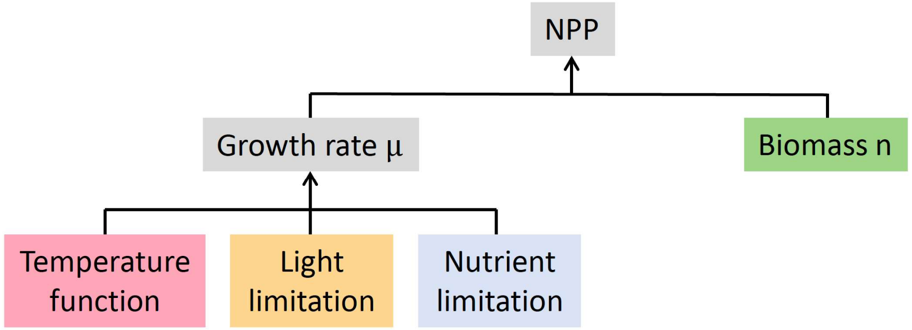


Le Grix et al. (2022, *Biogeosciences*)

Drivers of extremely low NPP during MHW-NPPX events

$$NPP = \mu\, n$$

$$dNPP = n d\mu + \mu dn$$



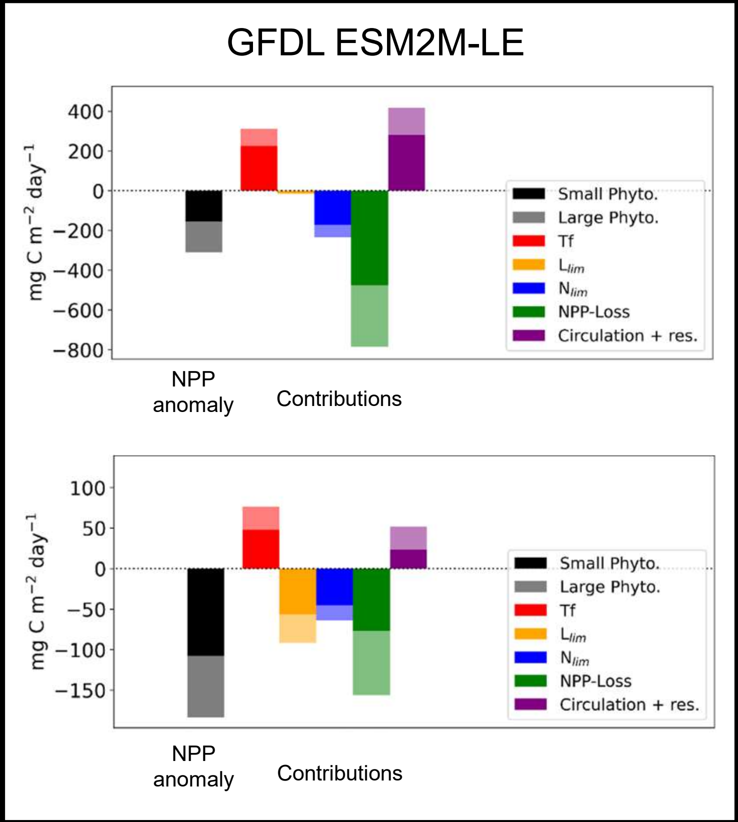
$$\mu = \mu_{max}\, T_f\ \ Irr_{lim}\ \ N_{lim}$$

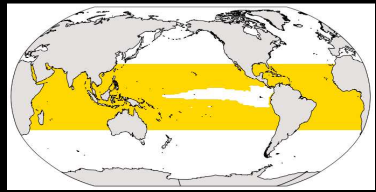
$$d\mu = \mu_{max}\, dT_f\ \ Irr_{lim}\ \ N_{lim} + \mu_{max}\, T_f\ \ dIrr_{lim}\ \ N_{lim} + \mu_{max}\, T_f\ \ Irr_{lim}\ dN_{lim}$$

→ Is low NPP driven by a change in Temperature? Light? Nutrients? Biomass?

Le Grix et al. (2022, *Biogeosciences*)

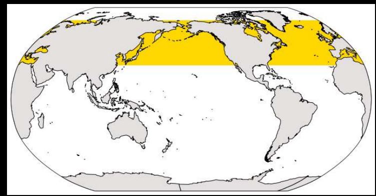
Drivers of extremely low NPP during MHW-NPPX





In the low latitudes:

- Lower growth because of nutrient limitation
- Lower phytoplankton biomass because phytoplankton loss (i.e. grazing) exceeds its production



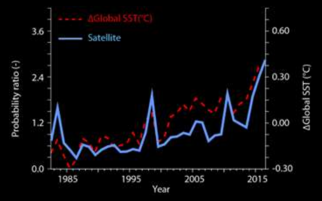
In the northern high latitudes:

- Lower growth because of nutrient limitation and light limitation
- Lower phytoplankton biomass because phytoplankton loss exceeds its production

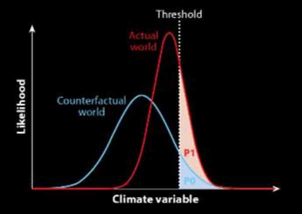
Le Grix et al. (2022, *Biogeosciences*)

Take-home messages

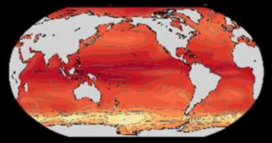
1. Marine heatwaves have doubled in frequency since 1982 and have become longer-lasting, more intense and more extensive.



2. Globally between 84-90% of marine heatwaves that have occurred between 2006 and 2015 are attributable to anthropogenic temperature increase. The Blob would have not occurred without human-caused global warming.



3. Marine heatwaves are projected to further increase in frequency, duration, spatial extent and intensity. Largest increases in frequency are projected for the Arctic and tropical oceans.



4. Biogeochemical extreme events, such as ocean acidity extremes, and compound events are also bound to strongly increase under climate change.