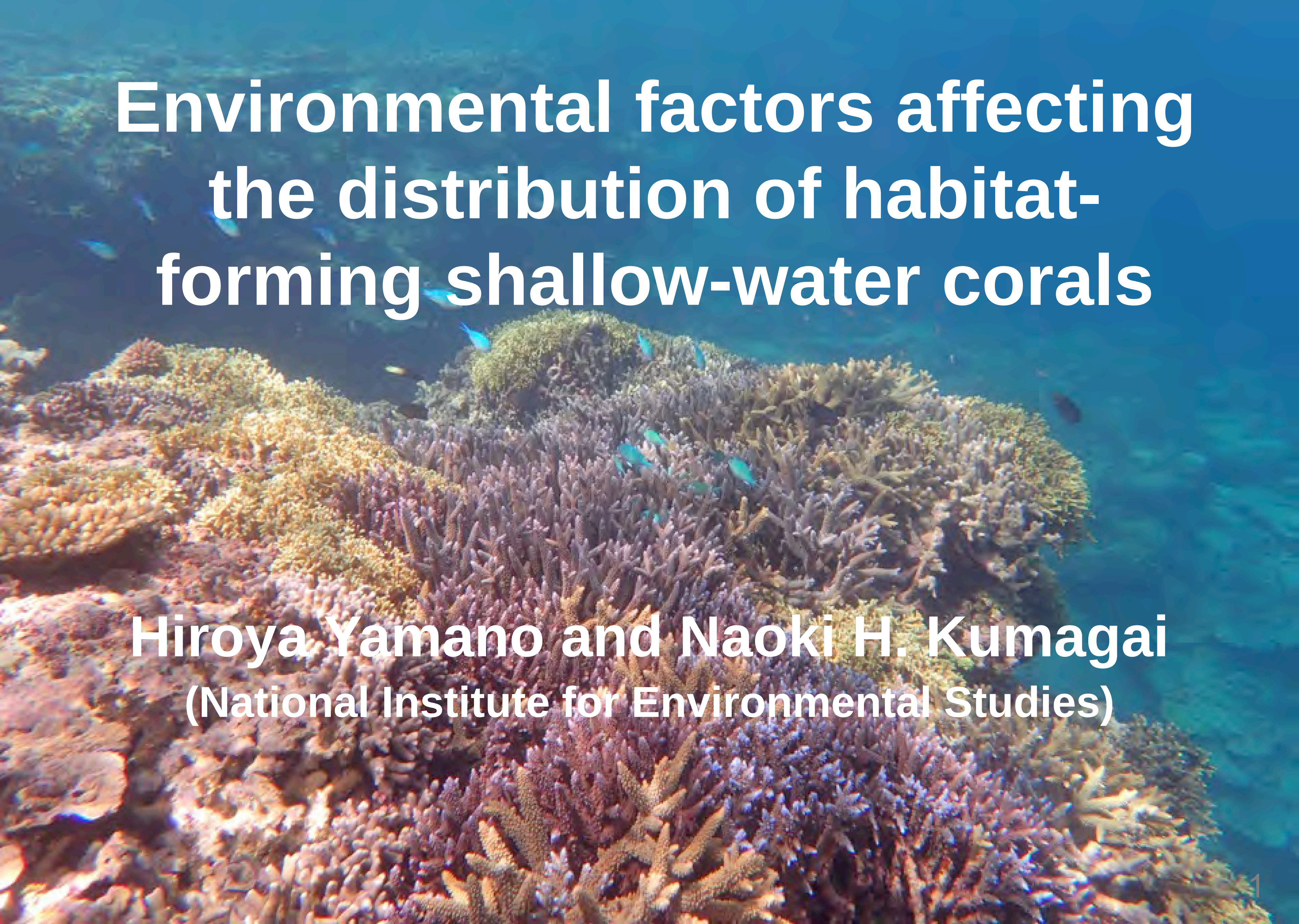
2-3/Nov/2016, PICES Workshop, San Diego

Environmental factors affecting the distribution of habitat-forming shallow-water corals



Hiroya Yamano and Naoki H. Kumagai
(National Institute for Environmental Studies)

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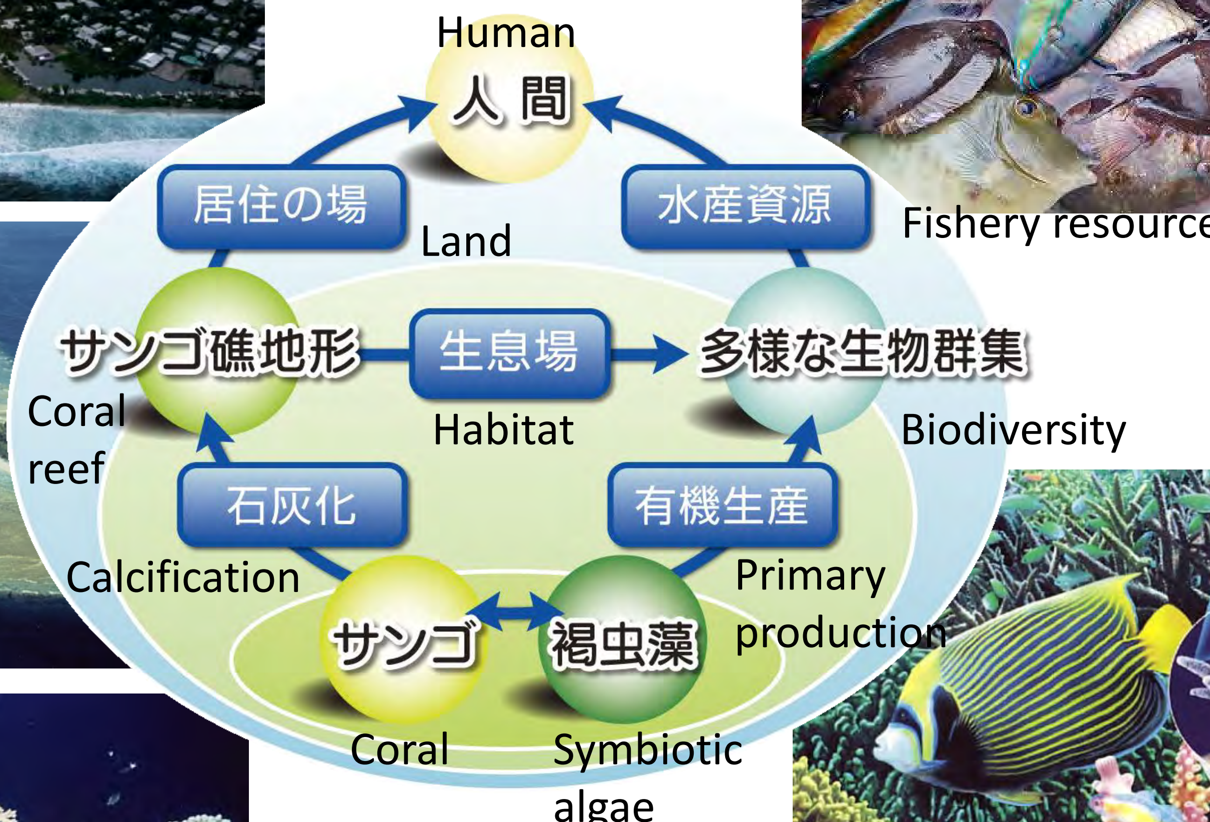
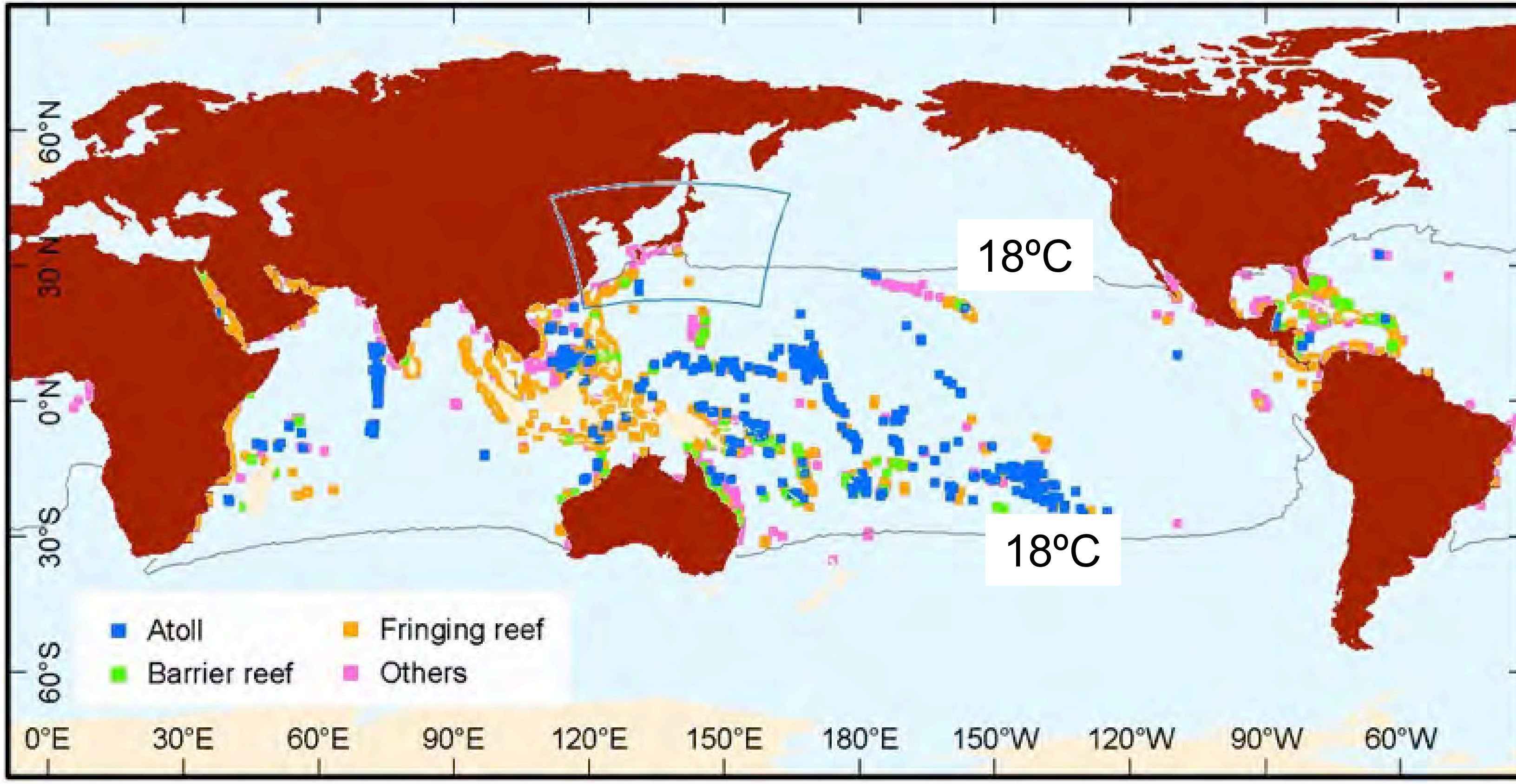

Human
人 間
居住の場
Land
水産資源
Fishery resource
サンゴ礁地形
Coral reef
生息場
Habitat
多様な生物群集
Biodiversity
石灰化
Calcification
有機生産
Primary production
サンゴ
Coral
褐虫藻
Symbiotic algae

Coral reefs of the world

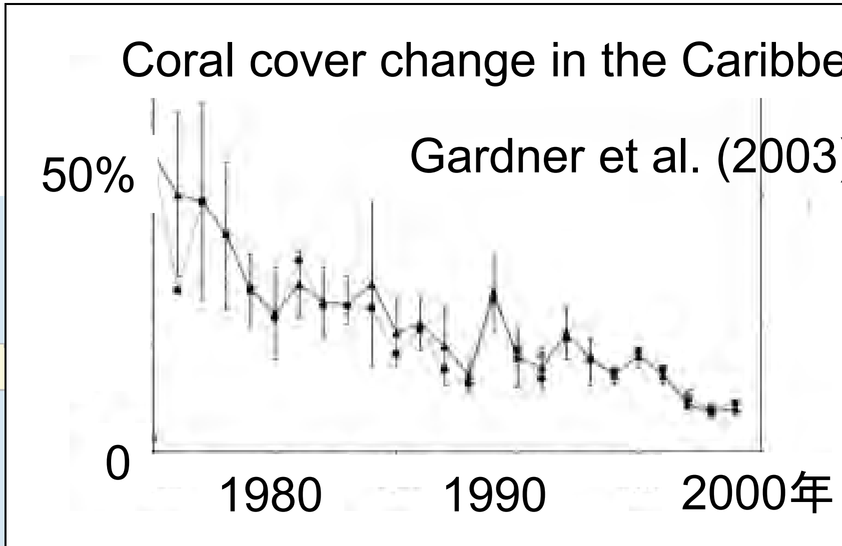


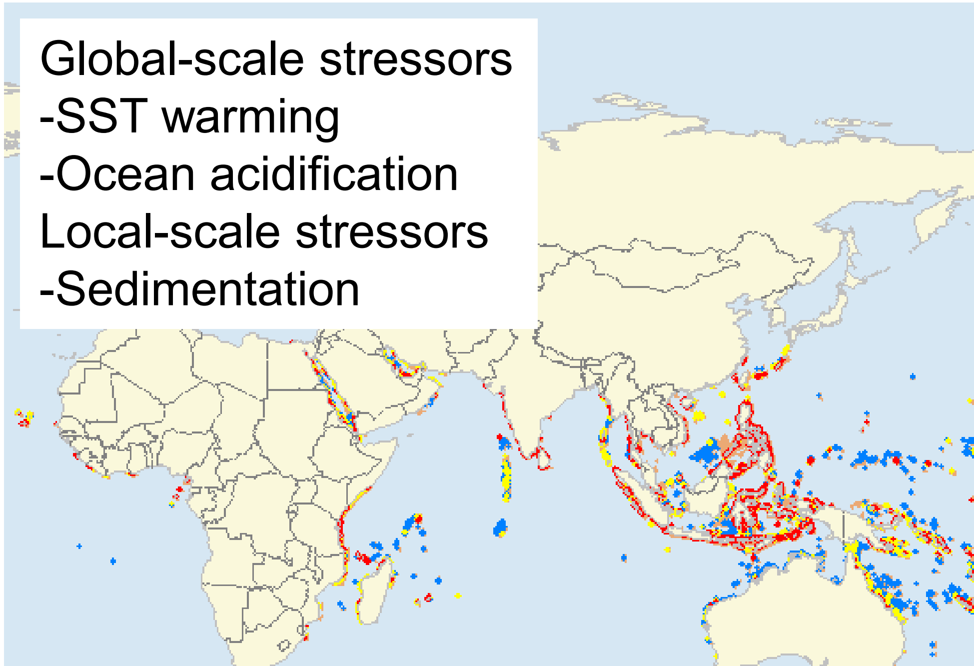
ReefBase (http://www.reefbase.org)

Japan:

- Transitional area (Subtropical - Warm Temperate - Temperate)
- Clear environmental gradient
- Less affected by continents
- Ideal setting to detect climate-induced effects

Recent changes in corals





Global-scale stressors
-SST warming
-Ocean acidification
Local-scale stressors
-Sedimentation

Red: High risk
Yellow: Medium risk
Blue: Least risk

Coral bleaching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Stories by subject
- Ecology

Stories by keywords
- coral
- coral reefs
- climate change

Published online 21 January 2011 | Nature | doi:10.1038/news.2011.33

News

Coral marches to the poles

Reefs may simply move house when the oceans heat up.

Nicola Jones

Corals around Japan are fleeing northwards, according to a new study. One type has been spotted 'sprinting' at 14 kilometres a year, thanks to a lift from ocean currents. That means ocean ecosystems could shift rapidly in the face of

Poleward range expansion

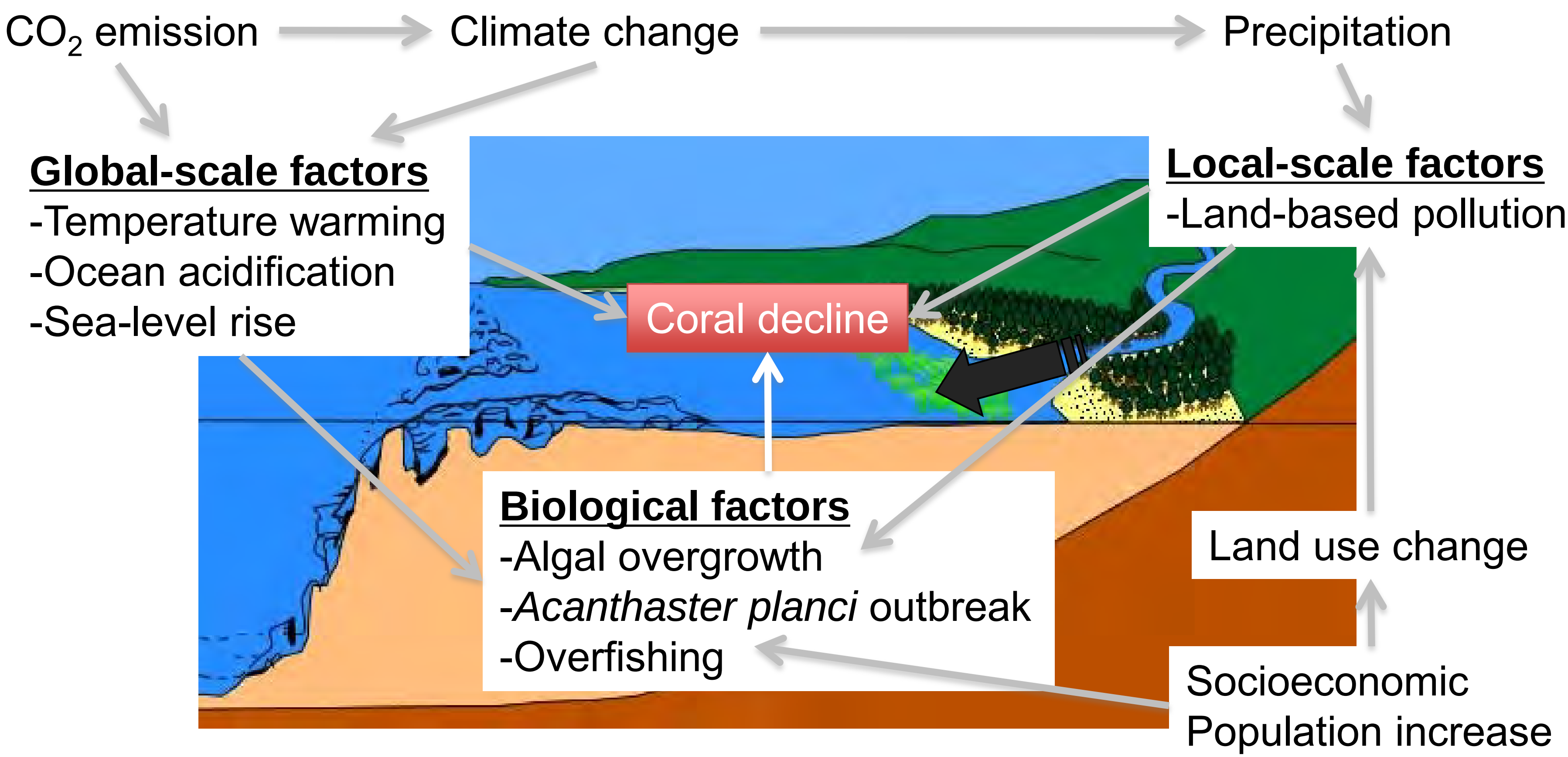
“Reefs at Risk”
(http://www.reefbase.org)

Aichi Biodiversity Targets

Target 10

By 2015, the multiple anthropogenic pressures on coral reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification are minimized, so as to maintain their integrity and functioning.

Multiple factors causing the distribution of corals



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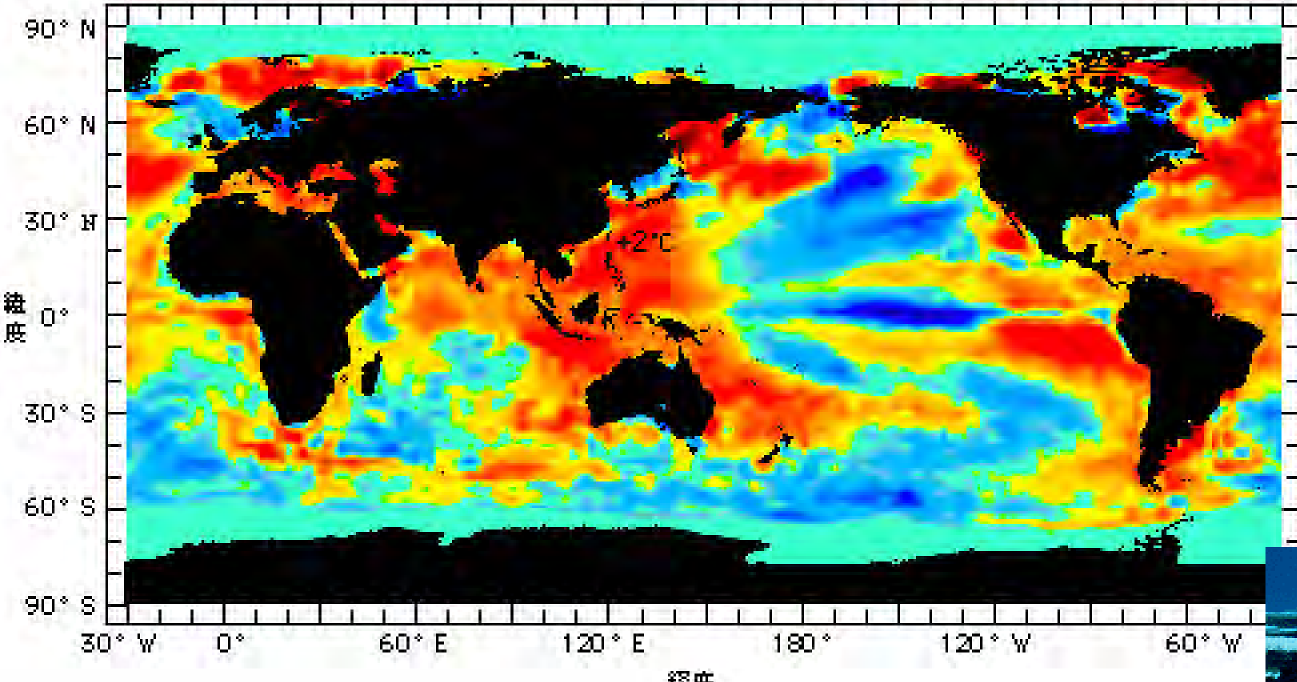
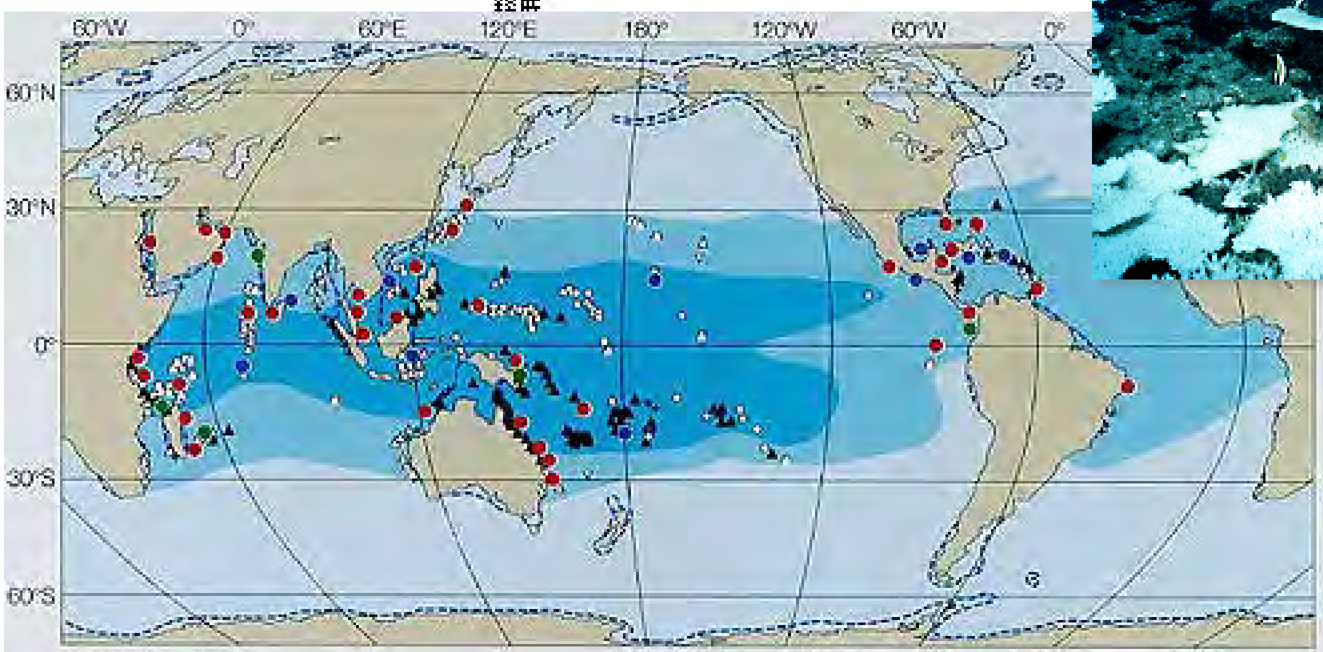
1998年夏の高水温とサンゴ白化

Anomalously high SSTs in the 1998 summer and coral bleaching





● 深刻な白化
Severe bleaching

日本サンゴ礁学会ウェブサイト（http://www.jcrs.jp/wp/?page_id=622)

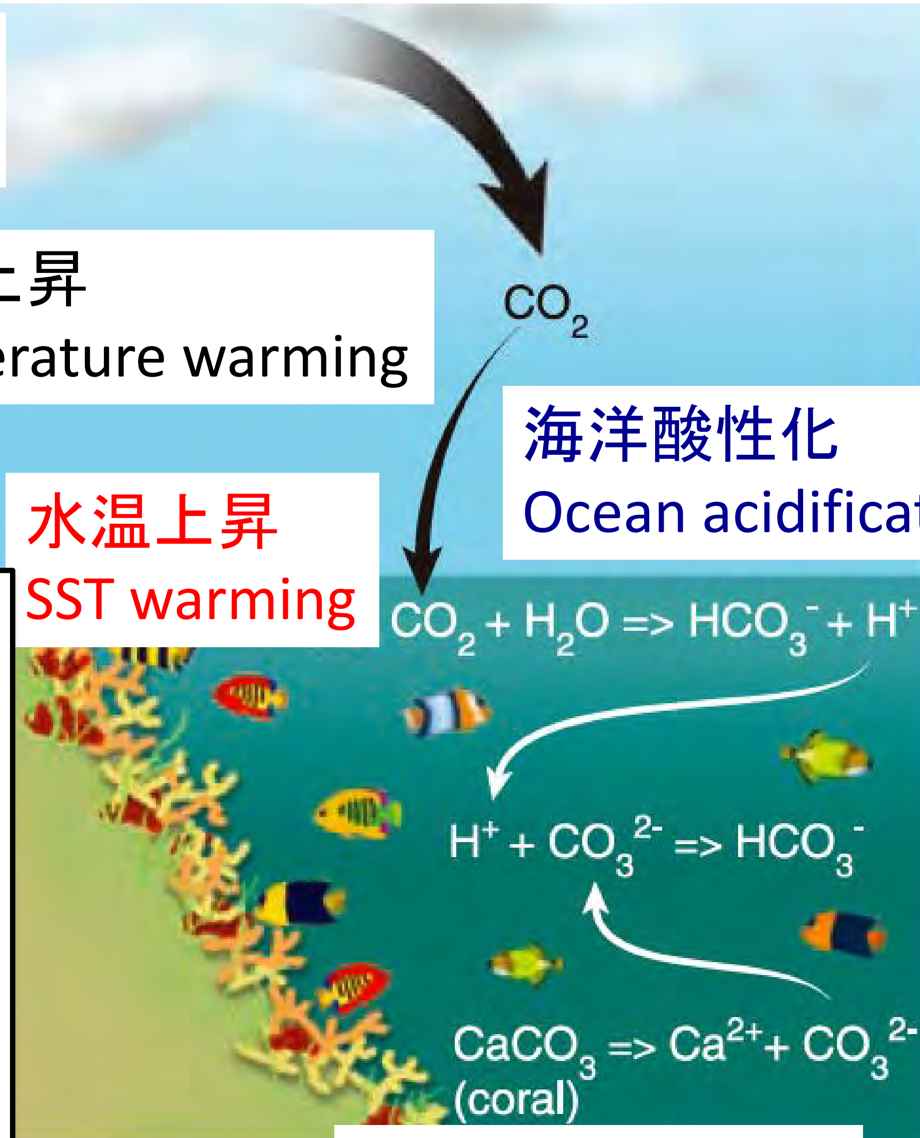
海洋酸性化ー地球温暖化と同時に進行するCO_2問題
Ocean acidification – Another problem related to CO_2 emission

温室効果ガス排出
Greenhouse gas emission

気温上昇
Temperature warming

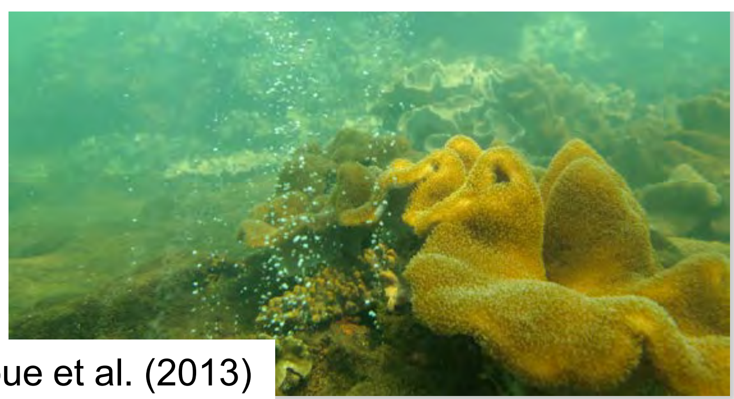
海洋酸性化
Ocean acidification

水温上昇
SST warming



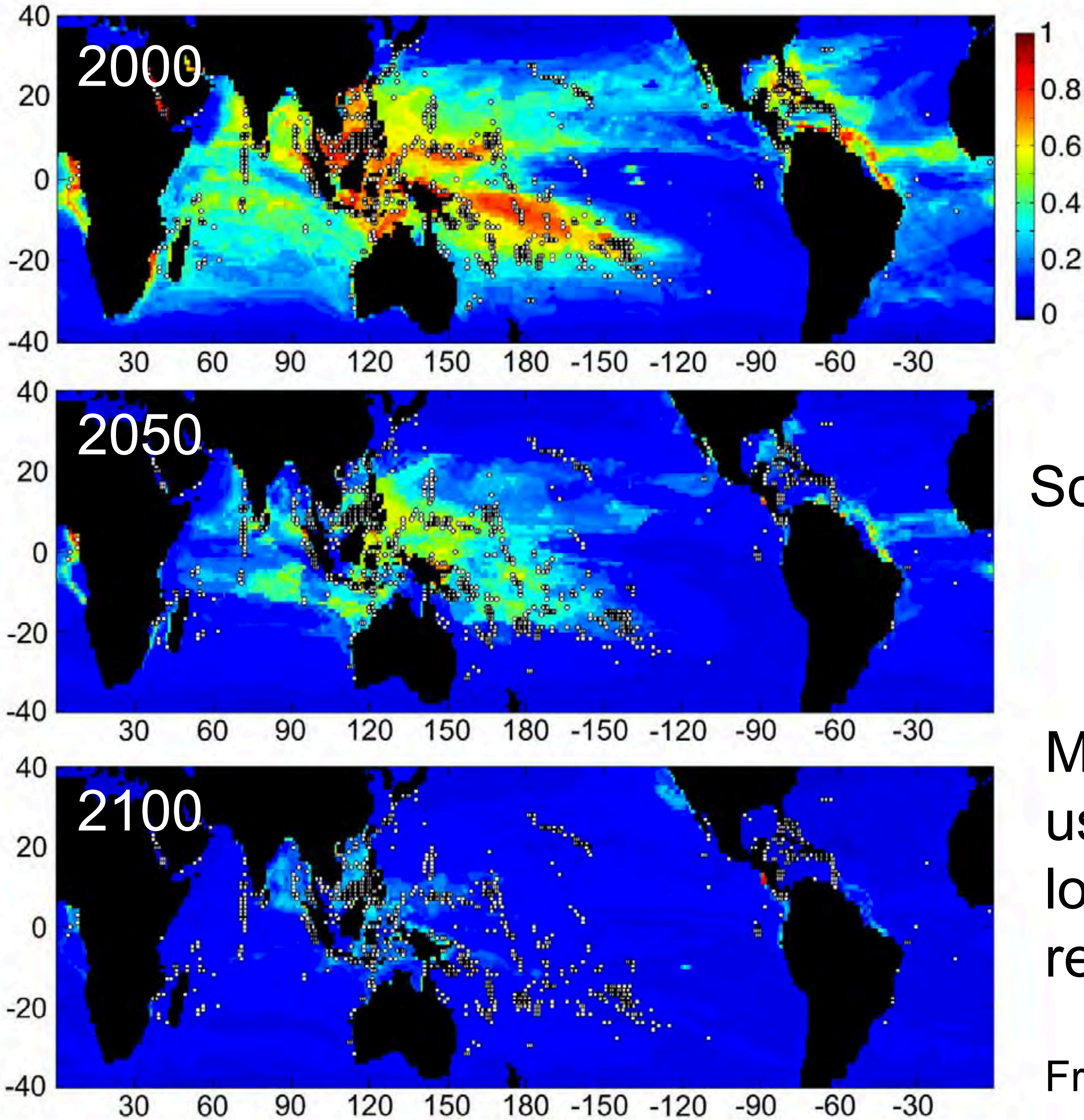
Hoegh-Guldberg et al. (2007)

海洋酸性化によりソフトコーラルに変化
Ocean acidification allow a community shift to soft corals



Inoue et al. (2013)

Future habitat suitability based on SST and ocean acidification

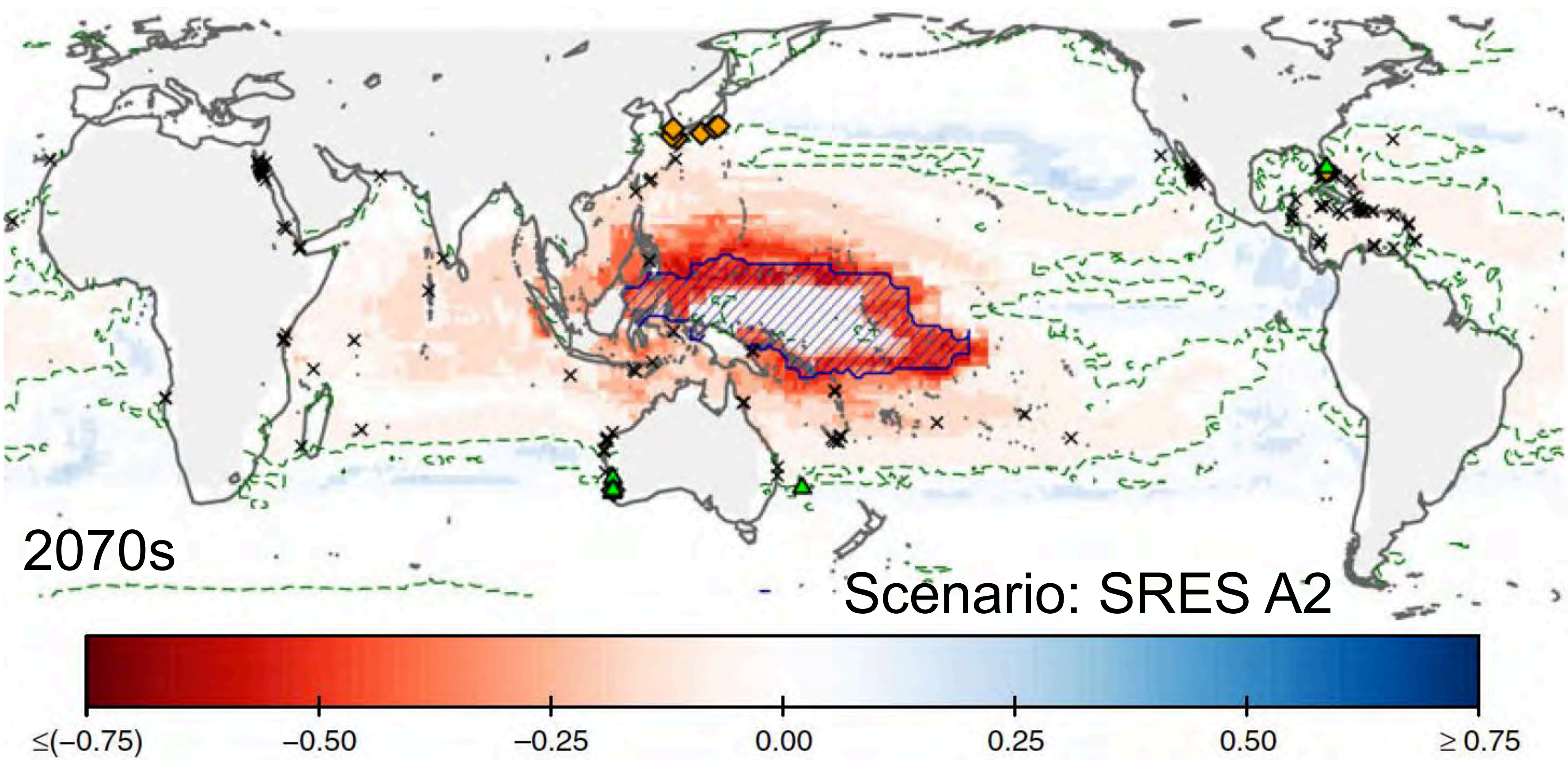


Scenario: RCP8.5

Maxent trained using the current location of coral reefs worldwide

Freeman et al. (2013)

Future habitat suitability based on SST and ocean acidification



Maxent and other models trained using the current location of coral reefs worldwide

Couce et al. (2013)

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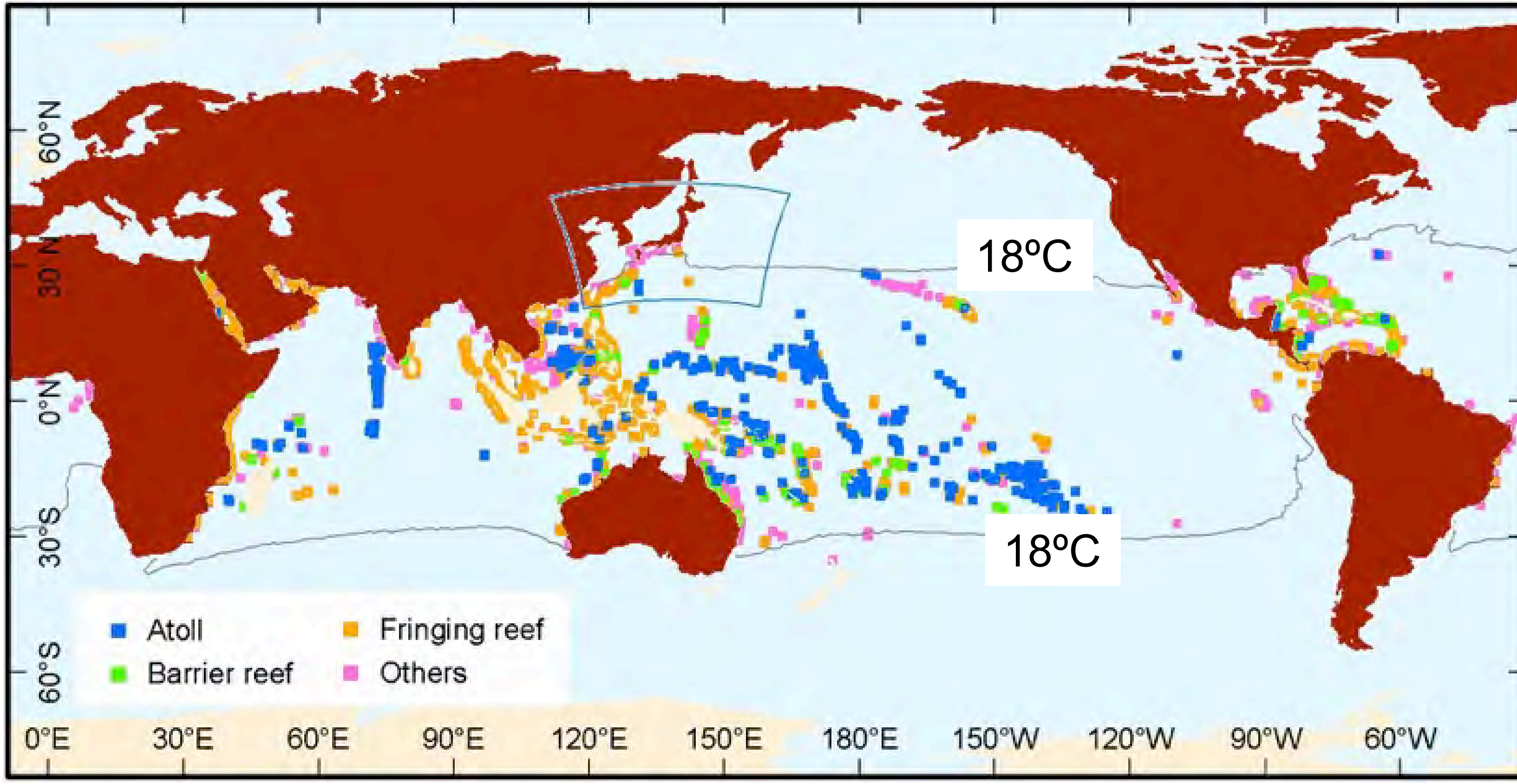
Coral reefs of the world

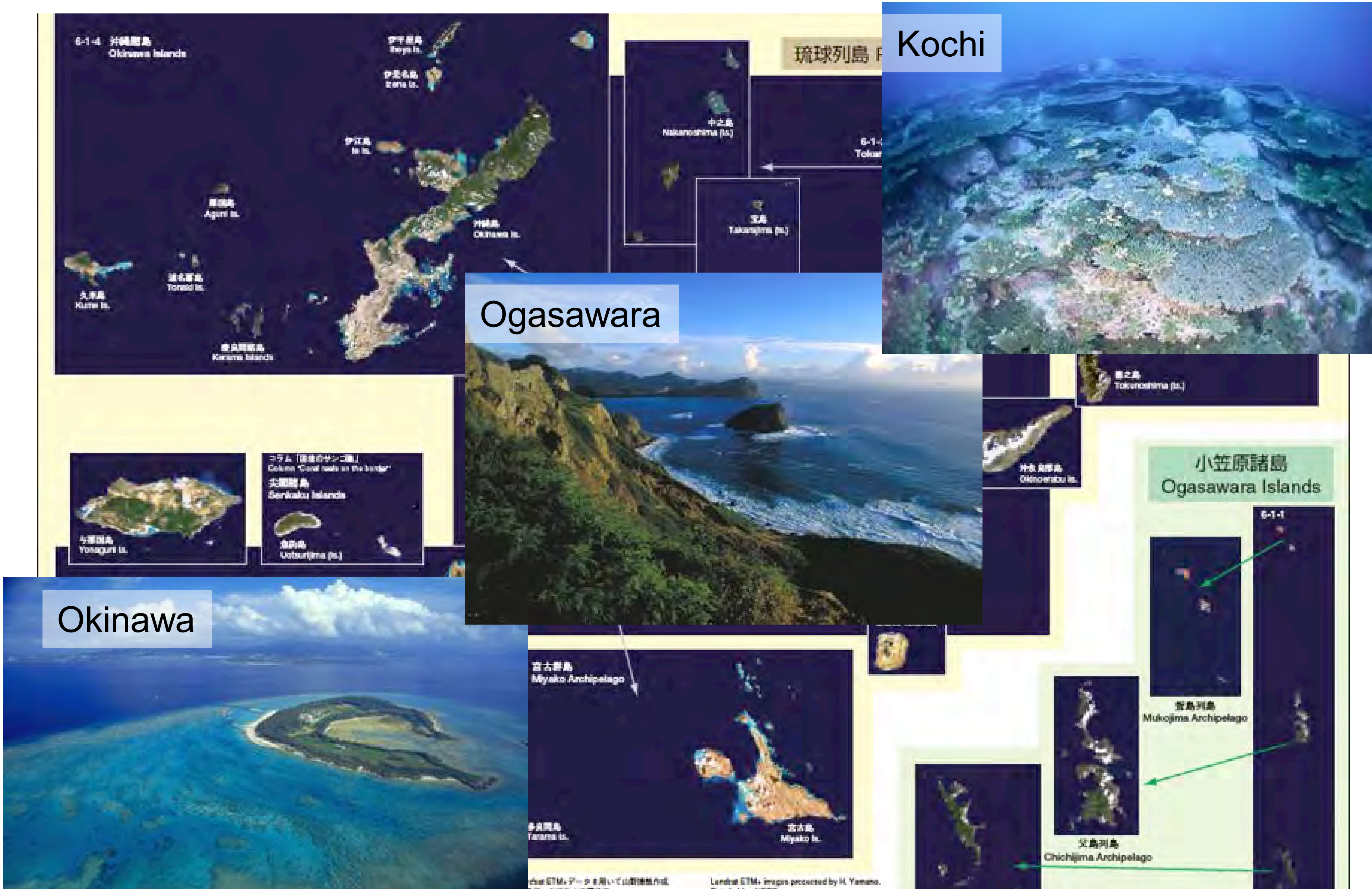


ReefBase (http://www.reefbase.org)

Japan:

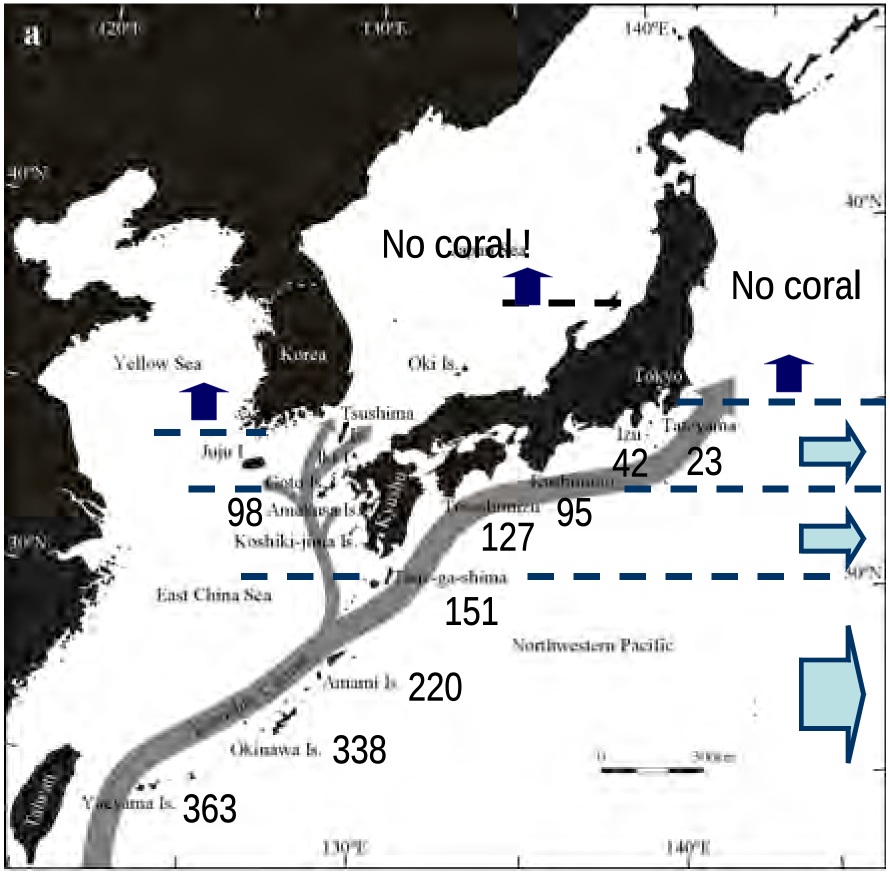
- ➢Transitional area (Subtropical - Warm Temperate - Temperate)
- ➢Clear environmental gradient
- ➢Less affected by continents
- ➢Ideal setting to detect climate-induced effects

Latitudinal gradient of coral reef geomorphology



Ministry of the Environment and Japanese Coral Reef Society (2004) Coral Reefs of Japan

Hermatypic coral fauna in Japan



◆composed mainly of the tropical fauna and the temperate fauna

◆has endemics in mainland Japan and adjacent Asian countries

◆divided into three major coral communities based on differences of species diversity (Veron 1992)

Outlying communities — Temperate fauna dominant

Non-reefal communities — 18°C

Coral reef communities — Tropical fauna dominant

◆coral species diversity in Japan decreases with increasing latitude

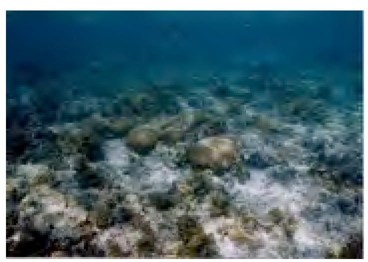
decrease in SST related to the Kuroshio Current (Veron and Minchin 1992)

Latitudinal changes in coral communities

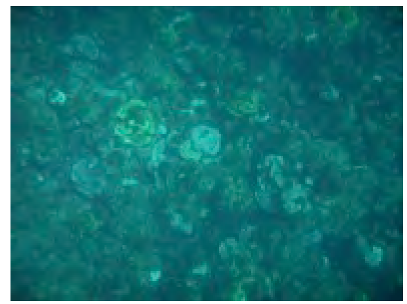
Coral reef community

Coral reefs are found widely

- ◆high cover and higher diversity, clear coral zonation correlated with reef topography and water depth gradient
- ◆branching *Acropora, Montipora* and *Porites,* and massive *Porites* and faviids dominant in shallow lagoons (<3m deep)
- ◆tabular *Acropora*, Robust-branching *Pocillopora*, and massive-encrusting faviids characterize upper reef slopes (<10m deep)
- ◆foliaceous-encrusting *Montipora* and pectiniids, and massive-encrusting faviids common at the intermediate depths (10-20m deep) on reef slopes
- ◆foliaceous-encrusting agariciids and *Porites*, and massive-encrusting faviids abundant on lower reef slopes (20-30m deep)

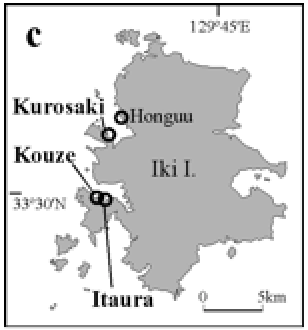
Non-reef community

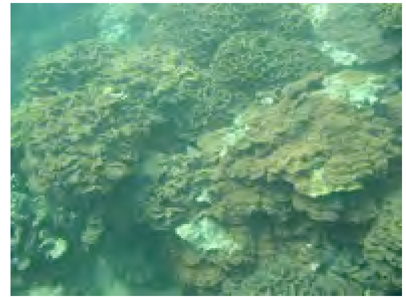


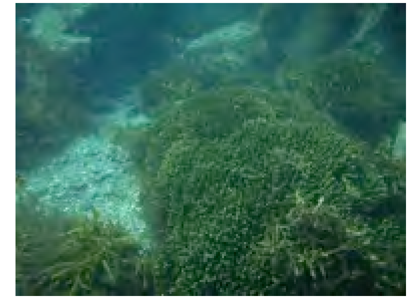
- ◆high cover and high diversity, unclear coral zonation
- ◆tabular *Acropora* dominant at the depths <10m (*A. hyacinthus > A. solitaryensis*)
- ◆associated with platy *Pavona decussata* and massive-encrusting faviids and *Porites* (mainly *P. heroensis*)
- ◆foliaceous-encrusting pectiniids dominant at the depths >10m associated with massive-encrusting faviids
- ◆blanching *Acropora* (*A. pruinosa,A. striata*?) also common in sheltered environments

No coral reef is found

Outlying community







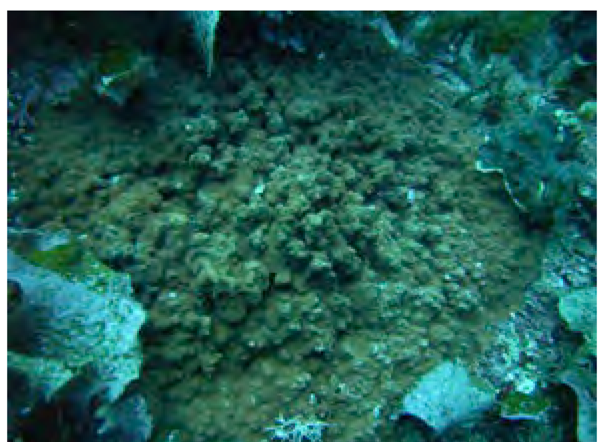
- ◆high cover but low diversity, clear coral zonation
- ◆no tabular *Acropora*
- ◆massive *Dipsastraea speciosa* and *Caulastrea tumida* dominant at the depths <2m
- ◆foliaceous-encrusting corals (*Echinophyllia* and *Lithophyllon*) dominant at the depths >2m
- ◆Massive *Oulastrea crispata* and *Alveopora japonica* inhabit the shallowest (<2m) and turbid areas
- ◆blanching *Acropora* (, *A. pruinosa*) also common

Extreme marginal corals

- Corals are distributed sparsely and do not form large communities
- *Oulastrea crispata* are distributed up to Sadogashima (37.5˚N), where monthly mean low SST is 10˚C

Endemic species

Oulastrea crispata



Psammocora profundacella

Alveopora japonica

Rising sea surface temperatures (SSTs)

SST warming in the last 50 yrs (Global)

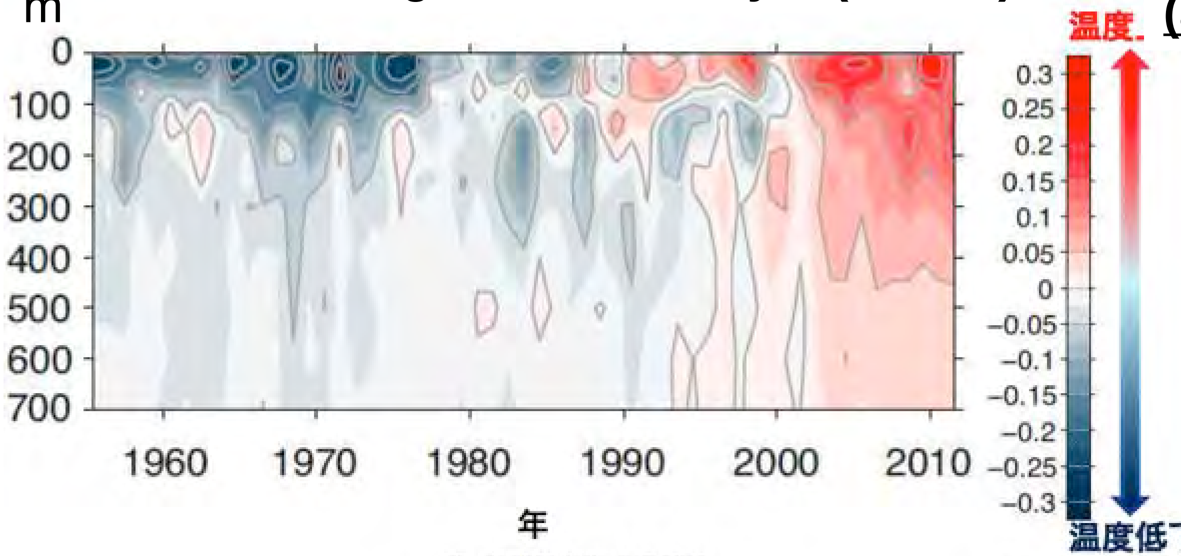
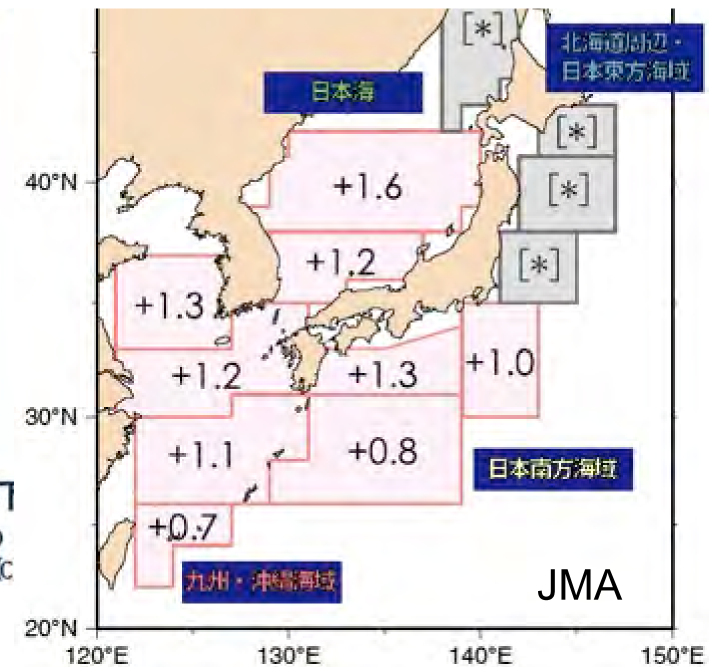


図. 全球平均海水温偏差
（1971年-2010年平均からの差）

IPCC AR5

SST warming in the last 100 yrs (around Japan)



JMA

Collecting past coral occurrence records

1930s
Specimen stored in
Tohoku Univ. Museum

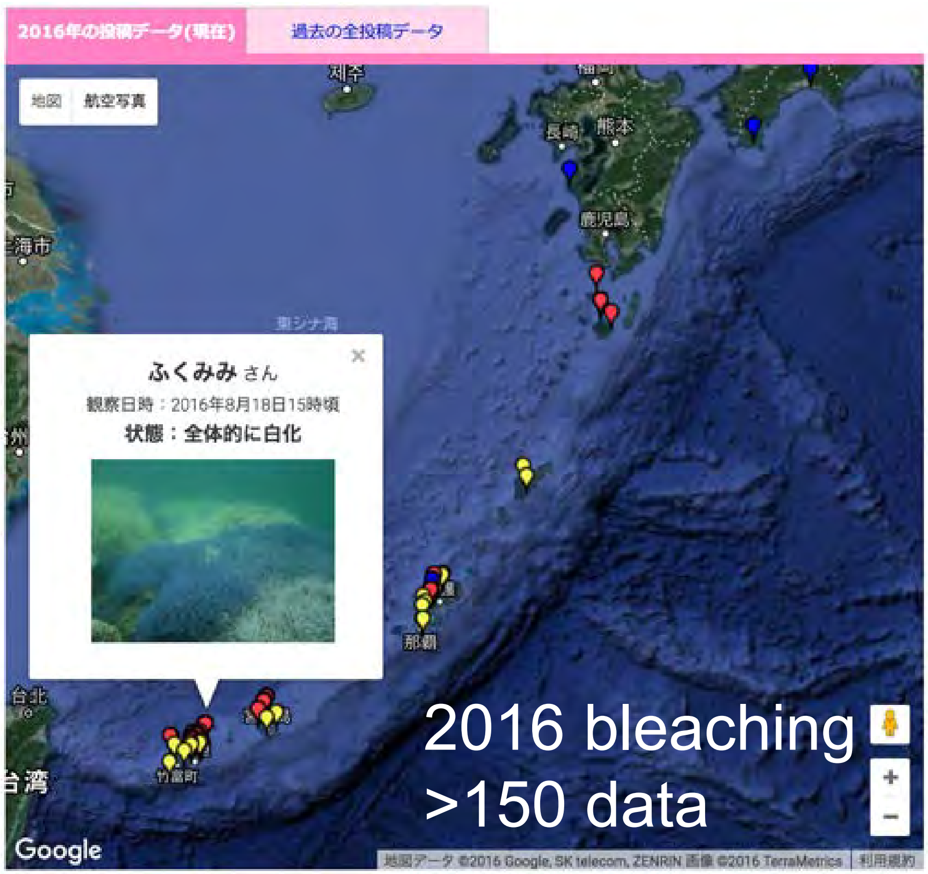
1960s-1970s
Survey reports to
designate marine parks

~30,000 records

1980s
Monograph
(Nishihira and Veron, 1995)

Citizen science enhances data abundance

http://www.sangomap.jp
2008~



サンゴの９割近くが白化

環境省調査35カ所 沖縄「石西礁湖」

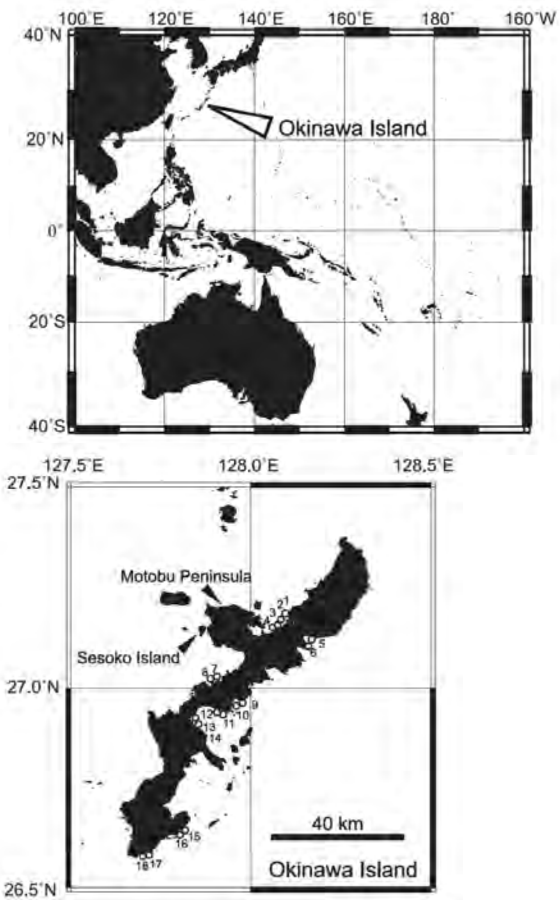
石垣島と西表島の間にある国内最大のサンゴ礁「石西礁湖」で起きている大規模な白化現象で、環境省が調査した35カ所で９割近くのサンゴが白化していることが27日分かった。

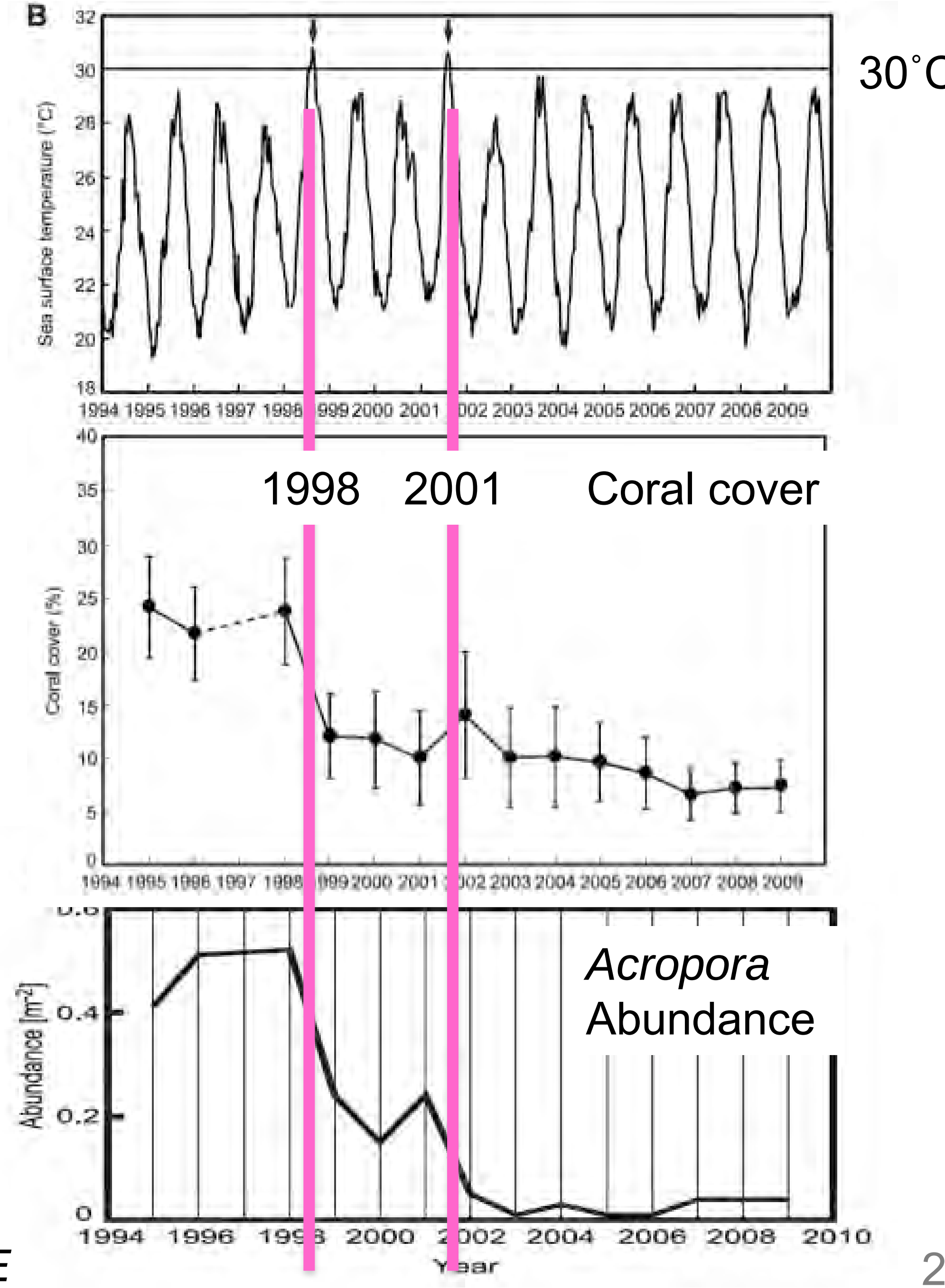
海水温の上昇が原因とみられ、石垣島の北部や鹿児島県の屋久島付近で白化が起きているとの報告もある。研究者や保全に取り組む市民団体はさらなる拡大を警戒。ダイバーらにサンゴの生息域や白化の状況などが投稿できるウェブサイト「サンゴマップ」への情報提供を呼び掛けている。

環境省那覇自然環境事務所は７月下旬から８月中旬にかけて、石西礁湖で水面近くからサンゴの健康状態を調査。高温や汚染などのストレスに弱いサンゴの一種ミドリイシに加え、ストレスに強いハマサンゴも一部が白化していた。

沖縄・石垣島の北端で８月18日に撮影されたサンゴの一種ミドリイシ。手前右と奥の部分が白化している（サンゴマップ提供）

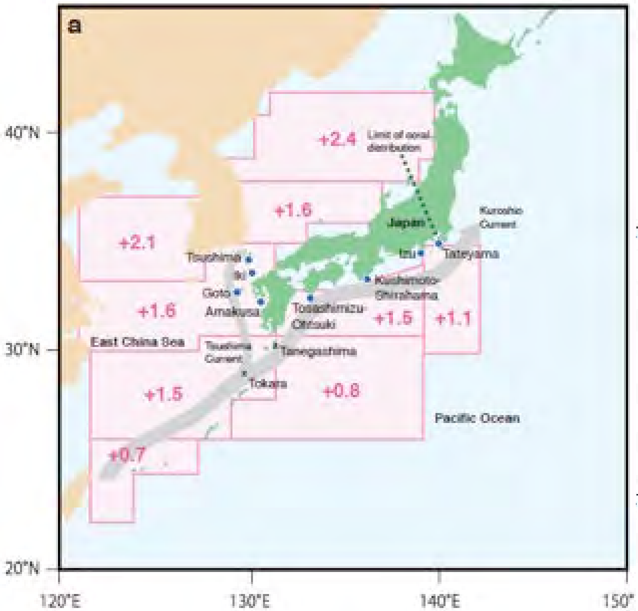
Recent coral decline due to bleaching at subtropical area

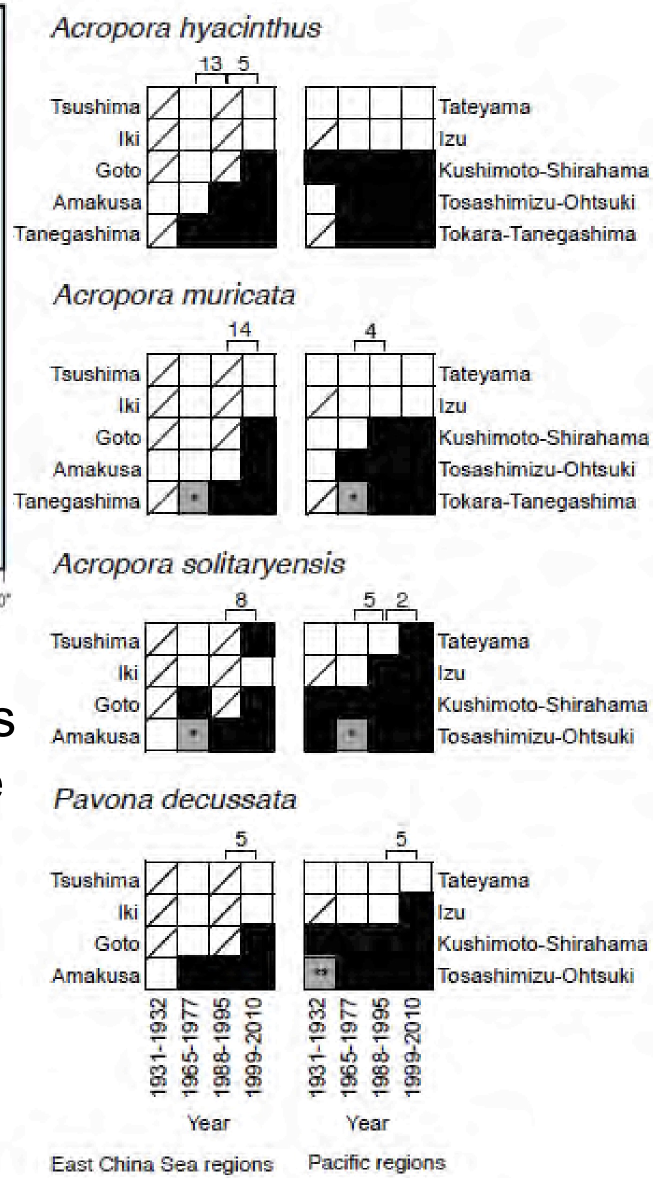




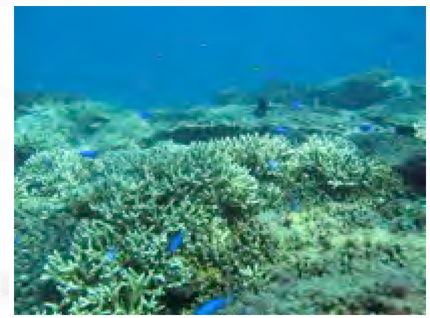
Hongo and Yamano (2013) *PLoS ONE*

Recent range expansion of corals at temperate area





A. hyacinthus@Goto



A. muricata@Goto

A. solitaryensis@Tsushima

Three subtropical species and one warm-temperate species showed range expansions
Speed: up to 14km/year

Yamano et al. (2011) *Geophysical Research Letters*

Consequences of the coral range expansion

Obligate coral-dwelling crabs were found on *A. solitaryensis* colonies that settled recently in temperate areas

Reef sites

Ranges of obligate coral-dwelling crabs extend northward as their hosts move north

Fig. 1 One of the northernmost *Acropora solitaryensis* colonies at Tateyama, Japan

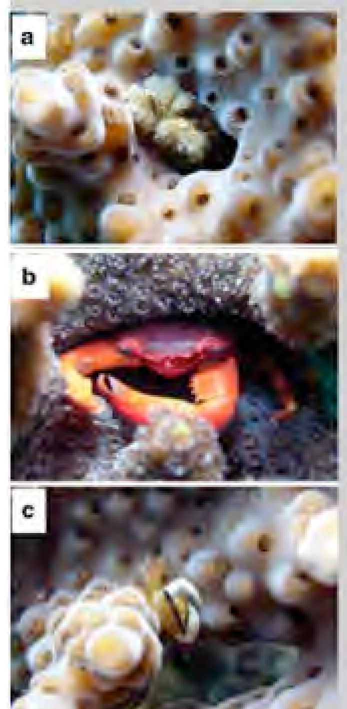


Fig. 2 Obligate coral-dwelling crabs associated with the northernmost *Acropora solitaryensis* colonies. **a** *Cymo melanodactylus*, **b** *Trapezia cymodoce*, and **c** Tetraliidae sp.

Recent sea-surface temperature warming may allow poleward range expansions of warm-water coral species into temperate areas. In Japan, *Acropora solitaryensis* Veron and Wallace, 1984 showed a poleward range expansion to Tateyama, on the southern tip of the Boso Peninsula (34°59′N and 139°47′E), based on the historical occurrence records and recent surveys (Yamano et al. 2011). The Boso Peninsula is located downstream of the Kuroshio warm current and is the northernmost known coral community in the Pacific, although it is located beyond the limit of the coral reef distribution (Shimoike 2004).

In July 2011, we observed five *A. solitaryensis* colonies on sedimentary rock substrate at water depths of ~12 m in Tateyama (Fig. 1). Four of the colonies served as hosts for obligate coral-dwelling crabs, *Cymo melanodactylus* Dana, 1852 (on one *A. solitaryensis* colony) (Fig. 2a), *Trapezia cymodoce* (Herbst, 1801) (on two colonies) (Fig. 2b), and Tetraliidae sp. (on one colony) (Fig. 2c). These were the northernmost records for *A. solitaryensis* and its associates *C. melanodactylus* and *T. cymodoce* in their distribution ranges (Minemizu 2000). The radius of *A. solitaryensis* colonies ranged from 6 to 15 cm, suggesting that settlement occurred several years between 1994 and 2004, according to the published radius expansion rate (0.9 cm/year; Yamano et al. 2011). Our observations suggest rapid establishment by crab symbionts after warm-water coral settlement, which may lead to changes in biodiversity in temperate areas during global warming.

Acknowledgments We thank Hitoshi Narita for field support. This research was supported by the Ministry of the Environment, Japan (Project No. S-9), and the Monitoring Project for Global Warming Effects on Marine Environments in the National Institute for Environmental Studies, Japan, and The Oceanic Wildlife Society.

References

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Shimoike K (2004) Boso Peninsula. In: Ministry of the Environment and Japanese Coral Reef Society (ed) Coral reefs of Japan. Ministry of the Environment, Tokyo, pp 232–233

Yamano H, Sugihara K, Nomura K (2011) Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. Geophys Res Lett 38:L04601. doi:10.1029/2010GL046474

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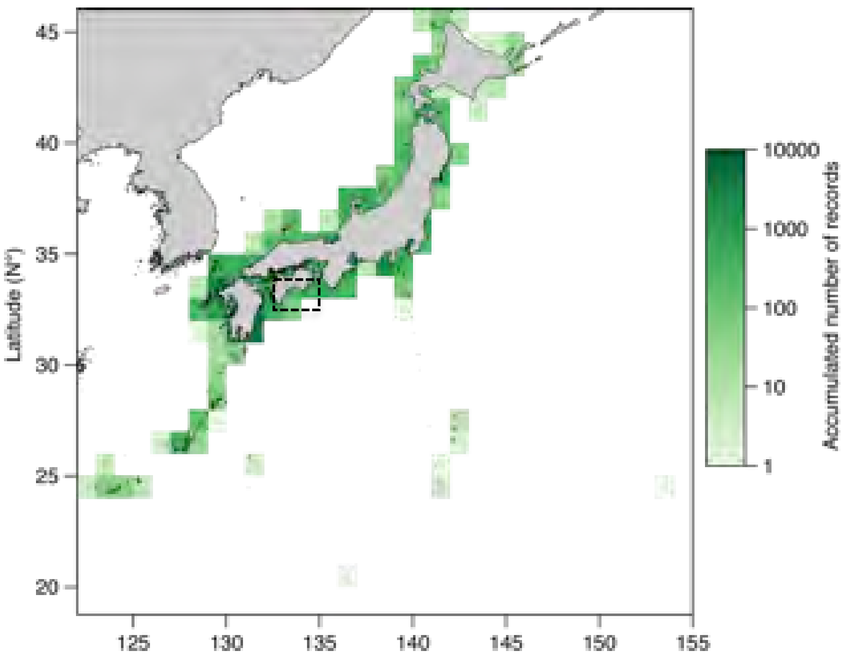
Received: 9 December 2011 / Accepted: 20 February 2012 / Published online: 3 March 2012
Coral Reefs (2012) 31:663
DOI 10.1007/s00338-012-0893-0

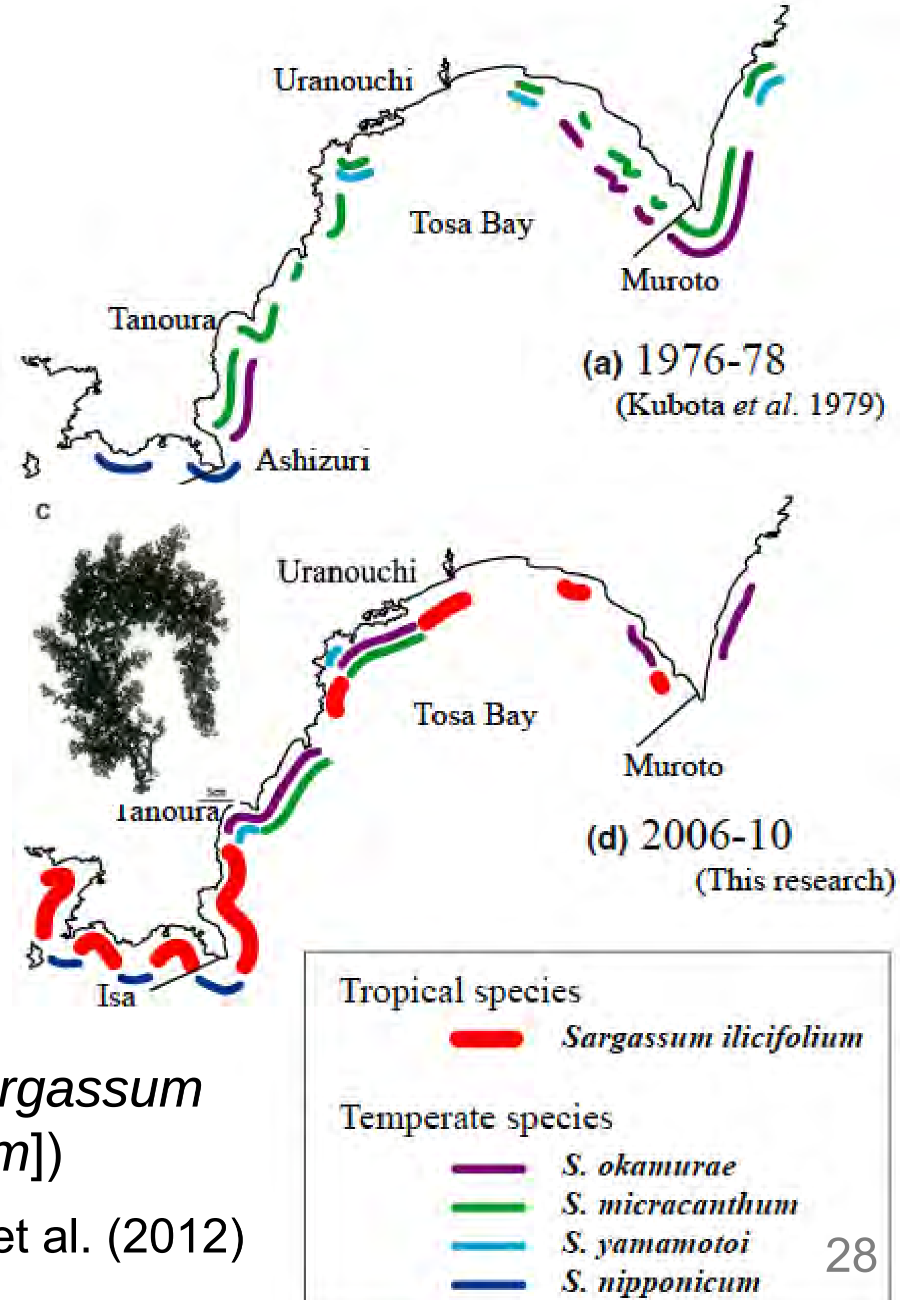
Yamano et al. (2012) *Coral Reefs*

Range expansion of subtropical seaweeds

Collection of seaweed occurrence records (1970s-; ~41,500 records)



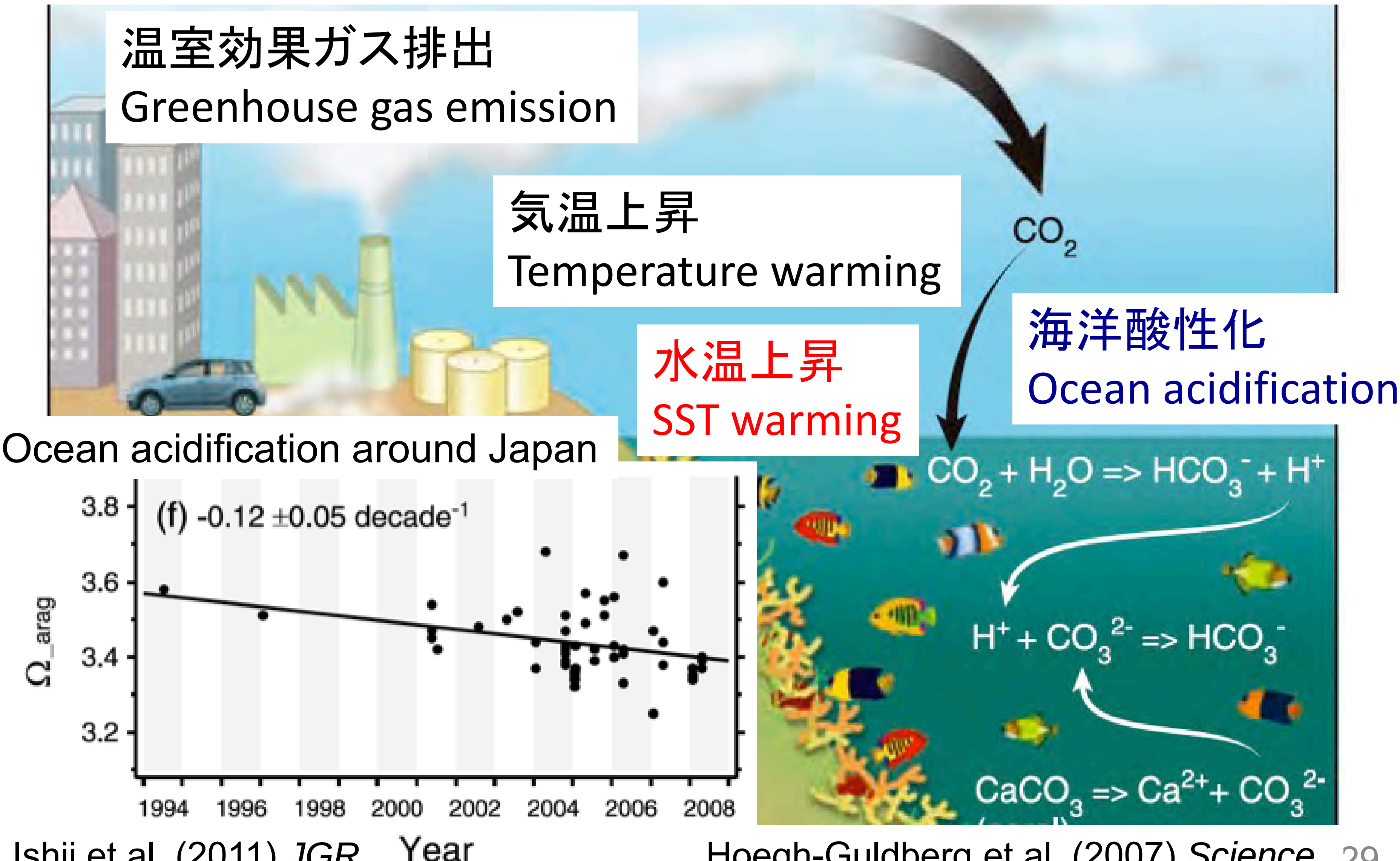
Kumagai et al. (submitted)



Range expansion of subtropical *Sargassum* (*S. ilicifolium* [formerly *S. duplicatum*])

Tanaka et al. (2012)

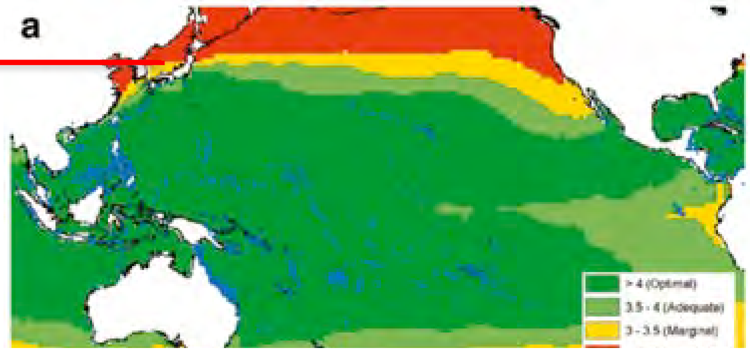
海洋酸性化ー地球温暖化と同時に進行するCO_2問題
Ocean acidification – Another problem related to CO_2 emission



Ishii et al. (2011) *JGR*

Hoegh-Guldberg et al. (2007) *Science*

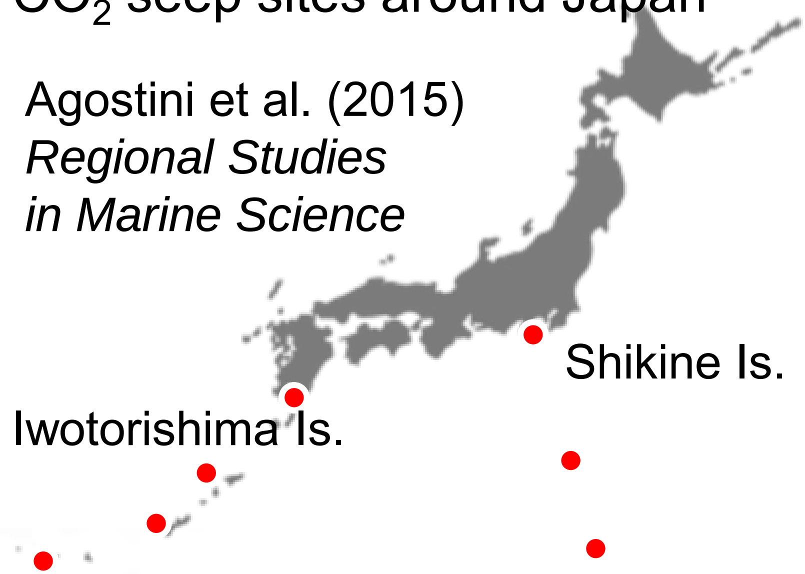
Another marginal feature: Aragonite saturation states



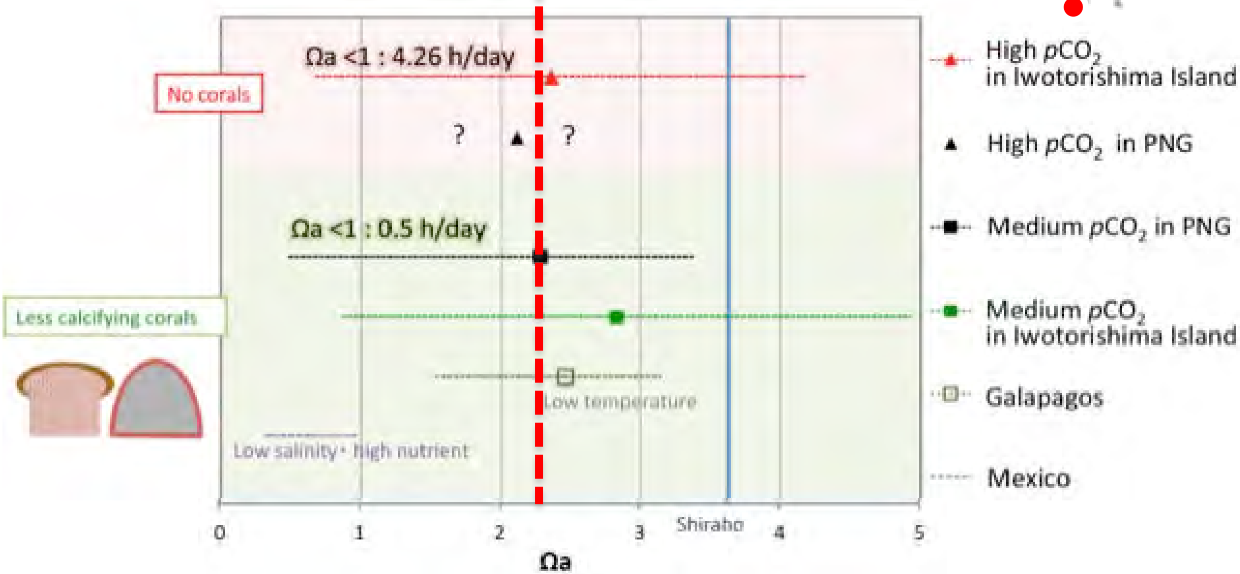
Guinotte et al. (2003) *Coral Reefs*

CO_2 seep sites around Japan

Agostini et al. (2015)
Regional Studies
in Marine Science



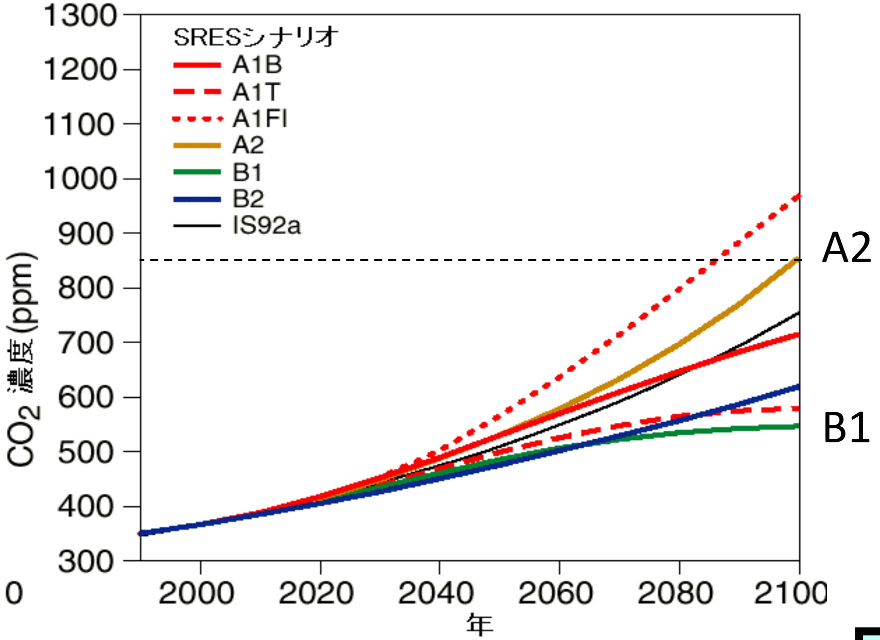
Threshold for coral occurrence: Ω=2.3?



Meta-analysis by Inoue (2015)

Inoue et al. (2013)
Nature Climate Change

気候モデルを用いた予測 Future projection based on a climate model



気候モデル Climate model

NCAR-CSM1.4

CO_2排出シナリオ
CO_2 emission scenarios

SRES A2 [高排出 business as usual]
SRES B1 [低排出 low emission]

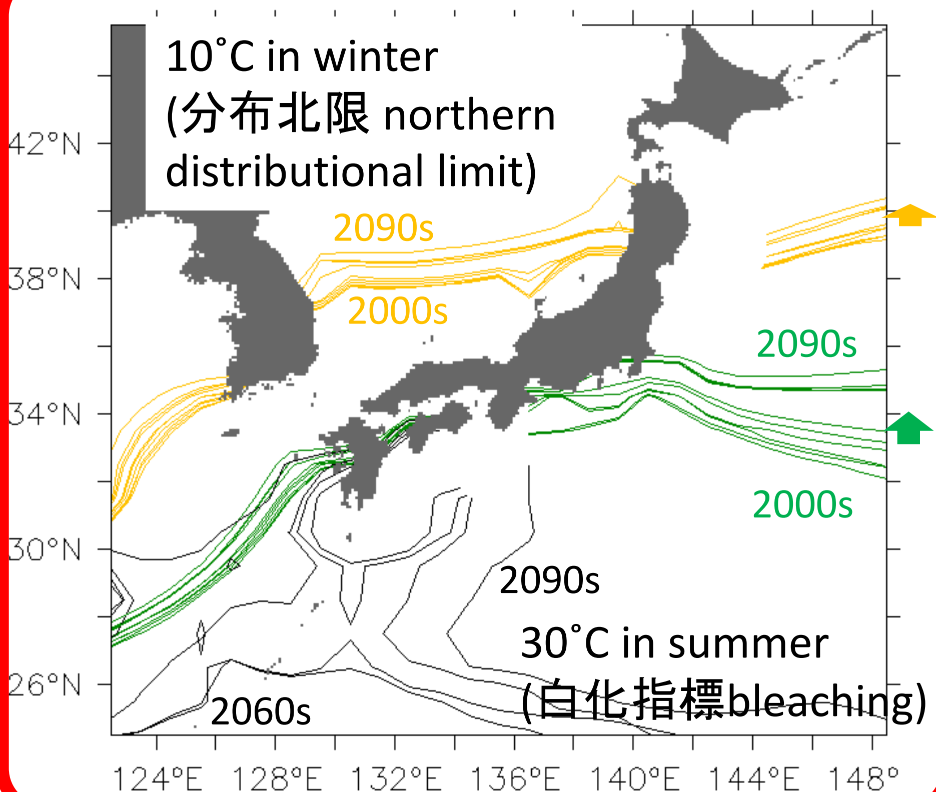
↓

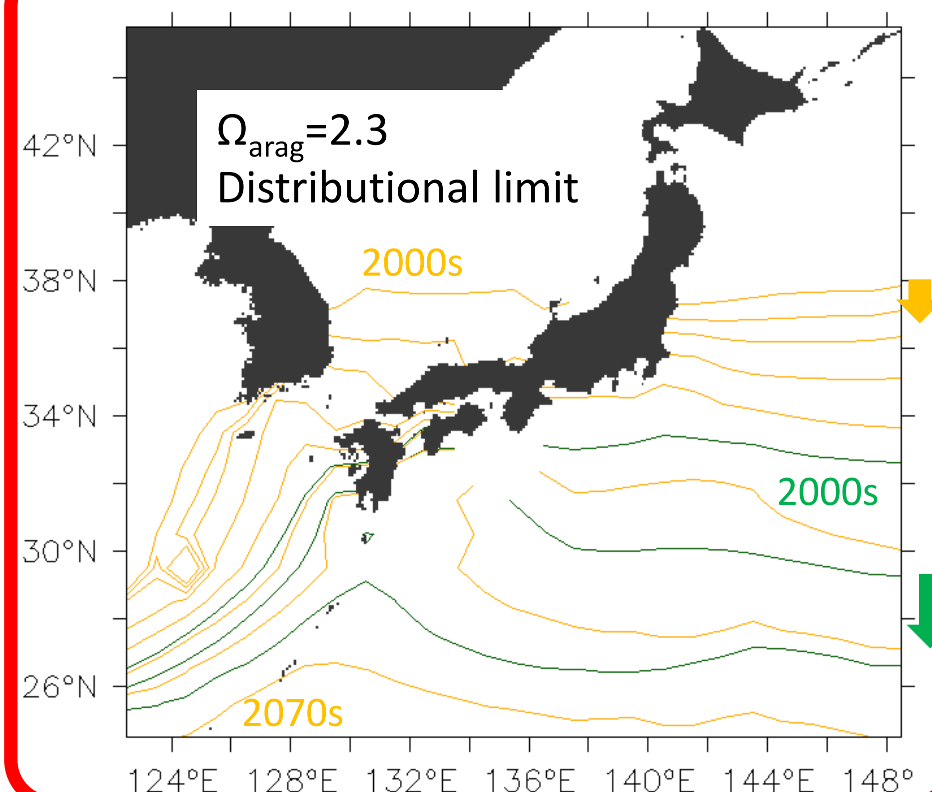
地球温暖化（水温上昇）と海洋酸性化（アラゴナイト飽和度）予測
Projection of global warming (SST warming) and ocean acidification (aragonite saturation state; Ω_{arag})

↓

将来のサンゴ分布域予測
Projection of future coral habitats

CO_2高排出(SRES A2) シナリオによる予測
Projection based on the business as usual scenario





<u>地球温暖化(水温上昇)</u>によるサンゴ分布変化
Coral habitat change due to SST warming

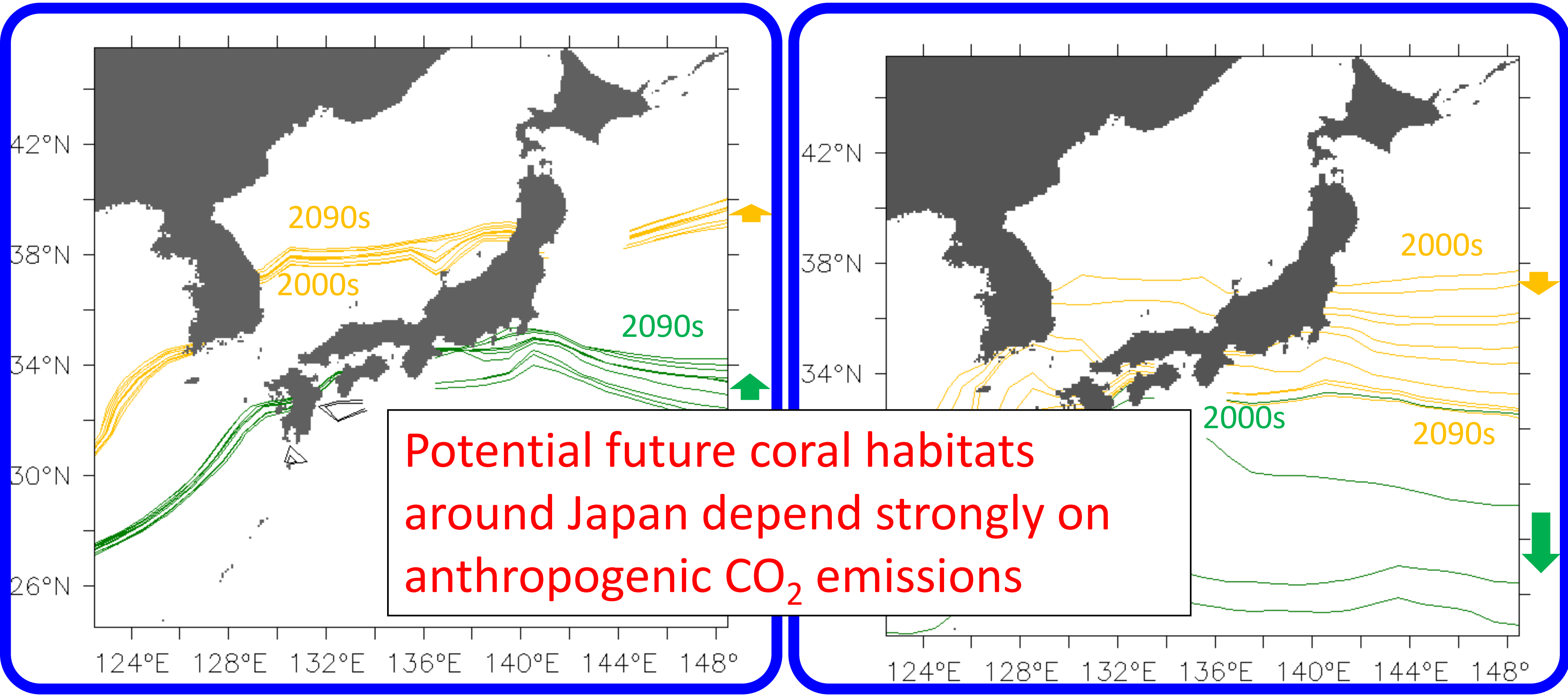
<u>海洋酸性化</u>によるサンゴ分布変化
Coral habitat change due to ocean acidification

高水温(夏の水温>30˚C)と海洋酸性化により、2070年代には日本近海からサンゴ消滅
Coral will disappear in the 2070s due to high SST and ocean acidification

Yara et al. (2012) *Biogeosciences*

CO_2低排出(SRES B1) シナリオによる予測

Projection based on the lowered emission scenario



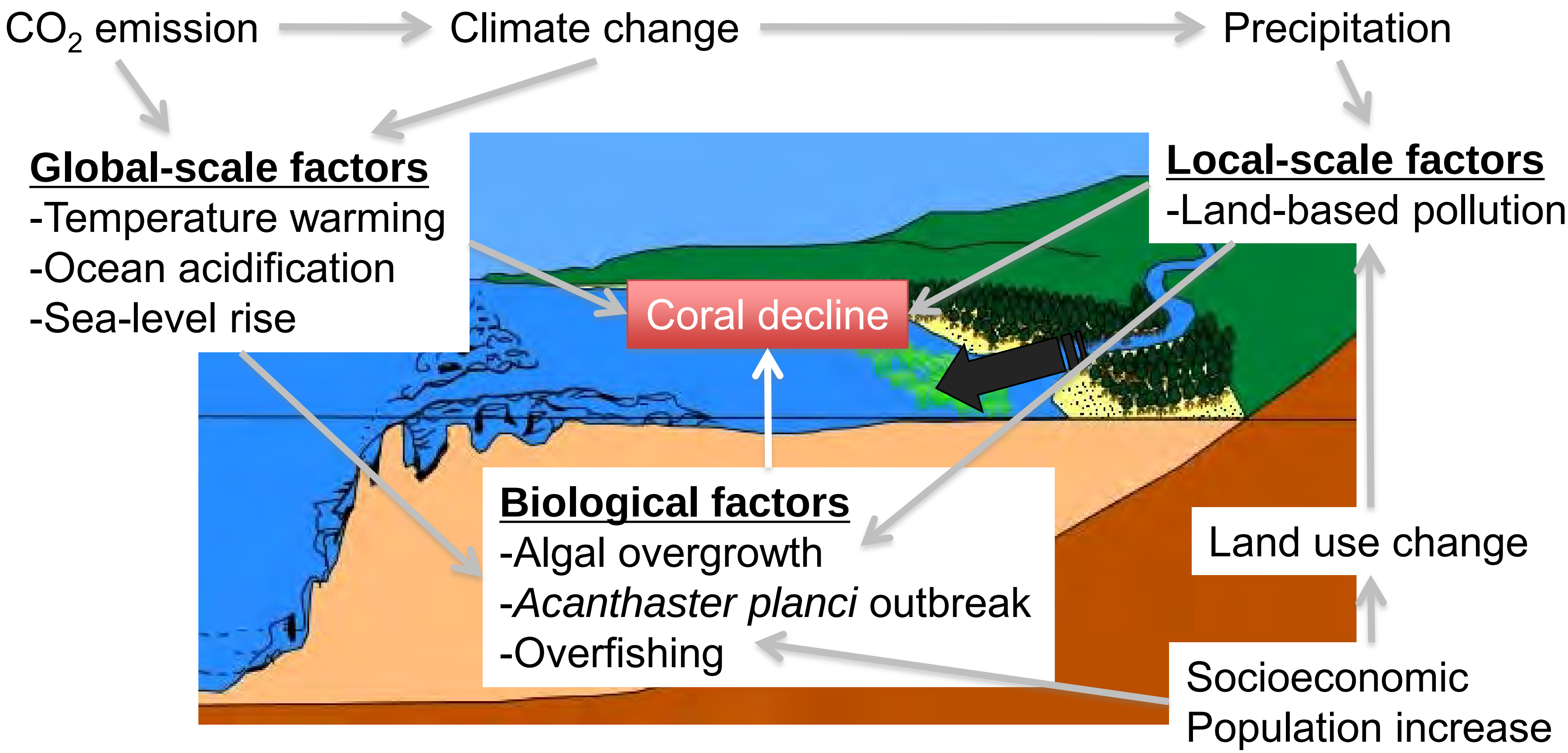
地球温暖化(水温上昇)によるサンゴ分布変化
Coral habitat change due to SST warming

海洋酸性化によるサンゴ分布変化
Coral habitat change due to ocean acidification

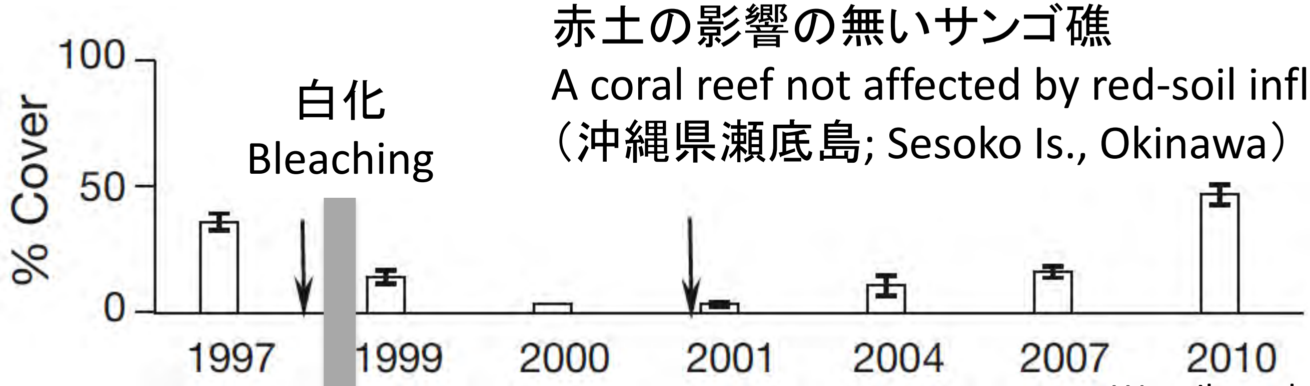
高水温は無く、海洋酸性化の影響は九州～四国まで
No bleaching, and the effect of ocean acidification would be limited to higher latitudes

Yara et al. (2016) In: *Aquatic Biodiversity Conservation and Ecosystem Services*

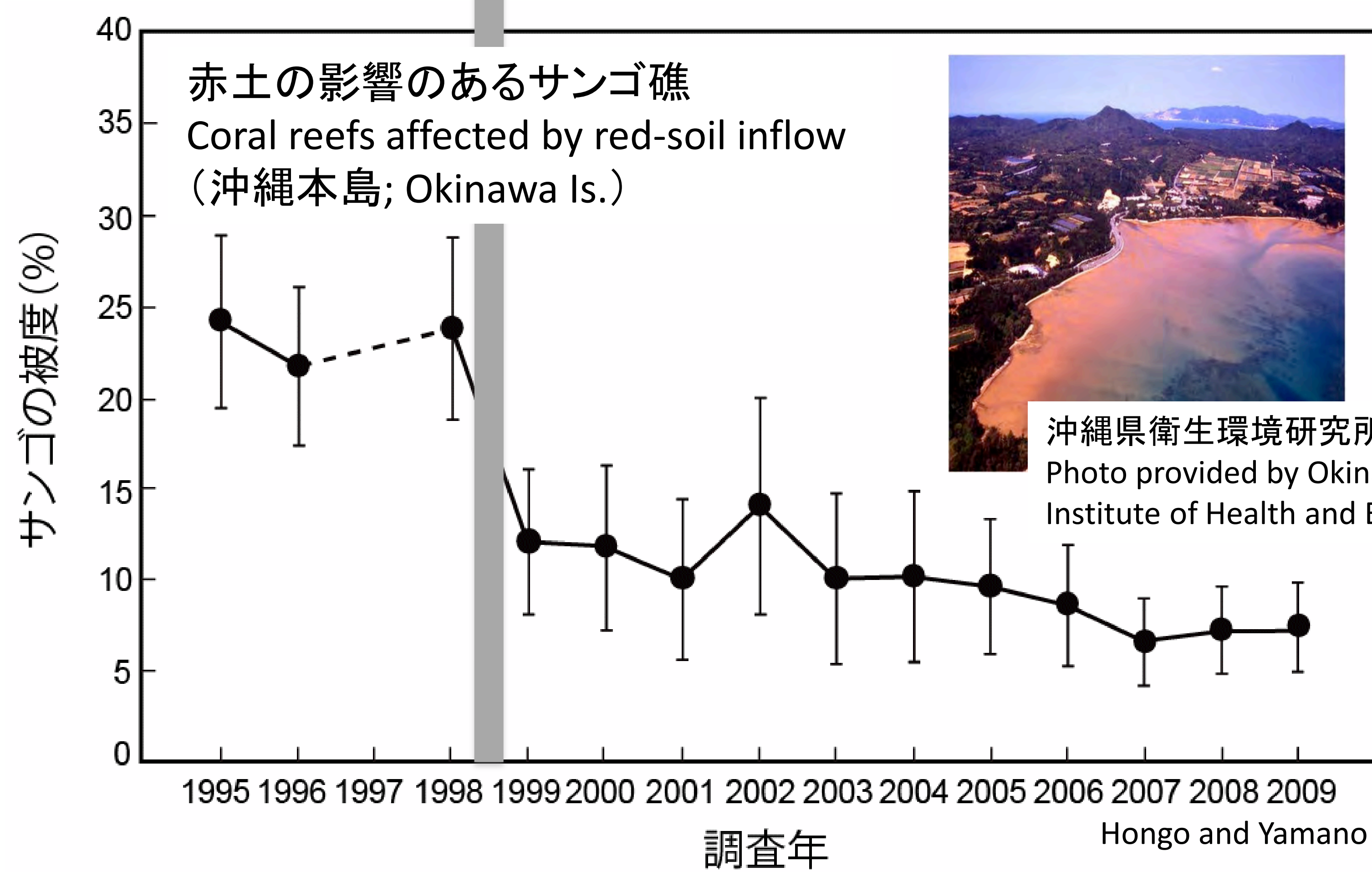
Multiple factors causing the distribution of corals



Sediment discharge from farmland



van Woesik et al. (2011)



沖縄県衛生環境研究所提供
Photo provided by Okinawa Prefectural Institute of Health and Environment

Hongo and Yamano (2013)

Conclusions

- Shallow-water corals are subject to multiple stressors at both global (SST warming and ocean acidification) and local (sediment discharge) scales
- Japan provides a unique opportunity (geographical setting and data abundance) to examine the relationship between environmental factors and corals
- Species Distribution Modeling may contribute to understanding the current/future coral distributions and set up conservation strategies to conserve corals

More on Species Distribution Modeling will be presented by Dr Kumagai

Predicting near-future changes in the distribution of temperate and tropical coral species in Japan

Naoki H. KUMAGAI (Nat. Inst. Envir. Stud., JP)

Check points in Species Distribution Modelings:

1. Dataset with less biases: sufficient range, balanced, presence/absence (e.g. "spatial sorting bias": Hijmans 2012 Ecology 93: 679–688)

–> Dataset across Japan over 50 years

2. Relative importance of temperature and other environmental factors (water and coastal characteristics) –> Multi-model

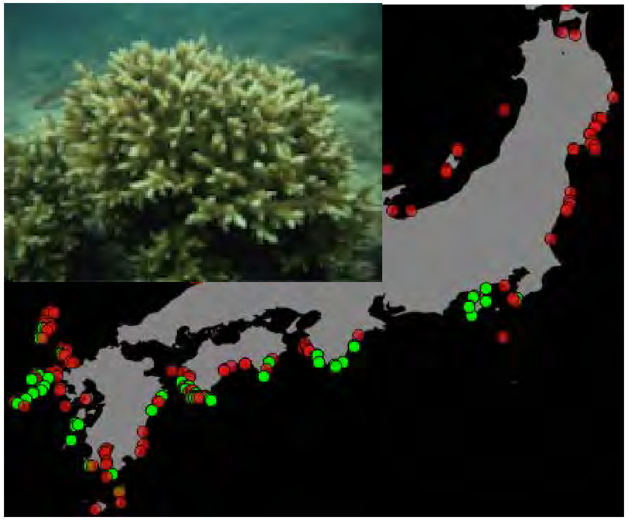
3. Multi-collineality: correlated patterns among explanatory variables (Dorman et al. 2013 Ecography 36: 27–46) –> Use of PCA score

4. Biases by specific statistical model –> Model ensembling of 7 statistical methods

Degradation of temperate seaweeds
Expansion of tropical corals

- Rising sea temperature –> physiology, herbivorous impact
- Overuse (terrestrial runoff, coastal development etc)

Study species: 2 groups of reef-building corals

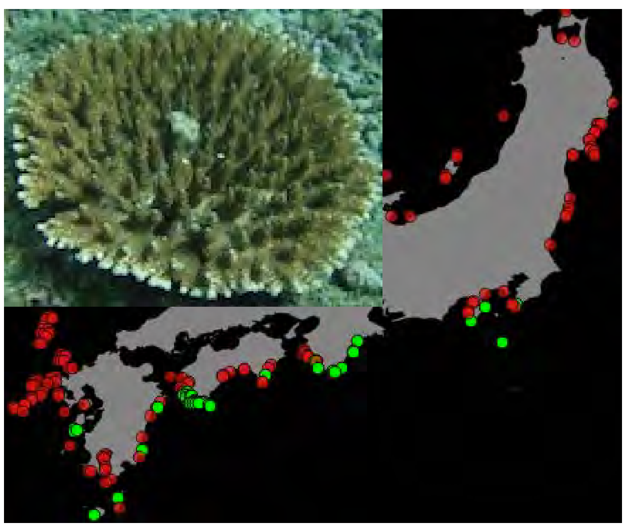


1. Temperate species (*Acropora pruinosa*)

- Sedentary species, not abundant

–> Less susceptible to thermal stress?

–> Range unchanged under temperature warming



2. Tropical species (*Acropora solitaryensis*)

- Expanding species into temperate zone

–> Responsive to thermal condition?

–> Range expansion under temperature warming

Materials & methods

- Collecting literature on historical records of occurrence

–> Summarize into GIS dataset

Compiling 9 environmental factors as explanatory variables

- Species distribution modelings

(statistical models + machine learnings)

–> Comparison: (1) sea temperature only model,

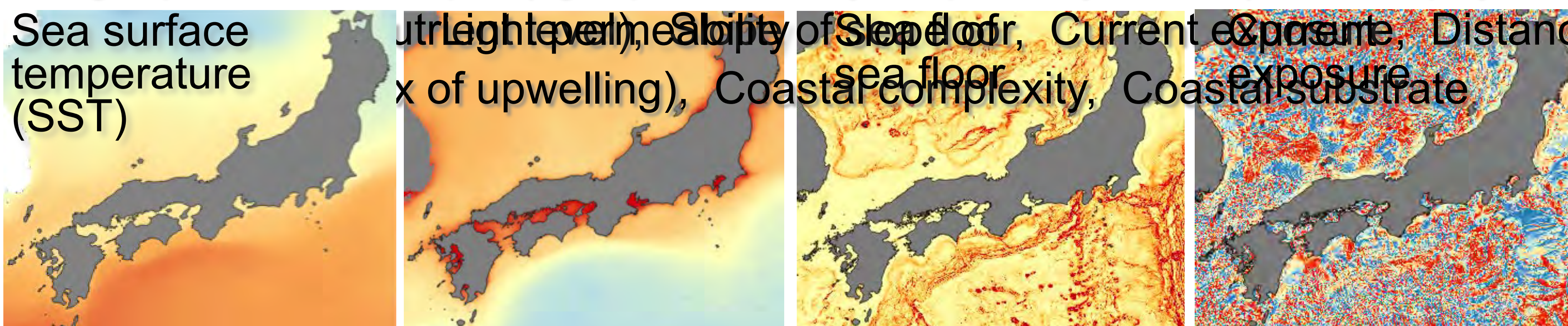
(2) temperature and water characteristics model,

(3) Full variables model (1, 2 and coastal characteristics)

–> Predictions for each decade period (1990s, 2010s, 2030s)

Environmental factors

- **Spatial resolution:** adjusted to 0.01°
- **Sea surface temperature (SST):**
  - Miroc4h model (0.28125°×0.1875°): 1950–2005 (historical) / 2006–2035 (only RCP4.5 provided)
  - Bias-correction with Optimum Interpolation Sea Surface Temperature (1986–2005)
  - Statistical interpolation with Multi-scale Ultra-high Resolution SST (0.01°, 2003–2012)
- **Other 7 variables** (used as constant)
  - Light penetration depth (light permeability for photosynthesis), Chlorophyll-*a*
  utrient level), Slope of sea floor, Current exposure, Distance
  x of upwelling), Coastal complexity, Coastal substrate



Species distribution modelings (SDMs)

1. 7 methods of SDMs using 9 explanatory variables
2. Prediction performances were evaluated with cross-validation
3. Predictions were ensembled to reduce model biases

("biomod2" in R)

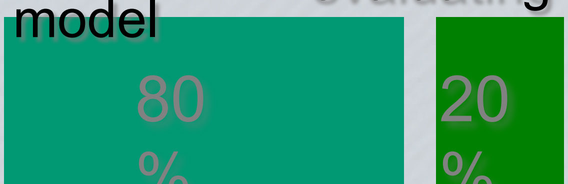
7 SDMs:

- Statistical models: GLM, GAM, MARS Multivariate additive regression splines
- Machine learnings: BRT Boosted regression tree, RF Random forest, ANN Neural network, Maxent

At each model running, data was split randomly –> repeat 10 times (cross-validation)

for building a model

for evaluating

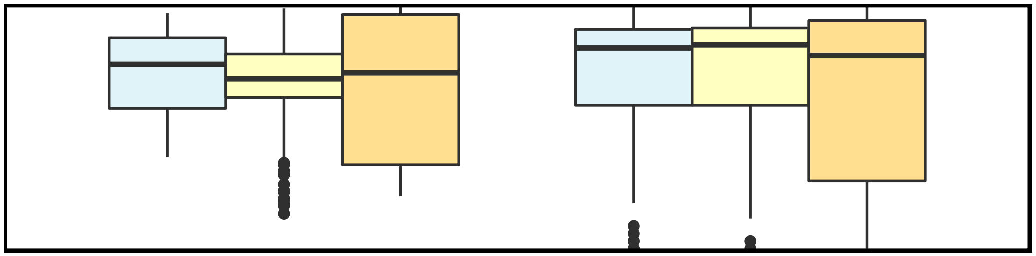


7 model methods x 10 cross-validations = 70 models

- Low performance models with AUC < 0.7 were avoided
  (AUC score was adjusted by the method of maximizing sensitivity + specificity)
- Ensemble selected models with weighting by their AUC scores

Comparing performances of SST indices

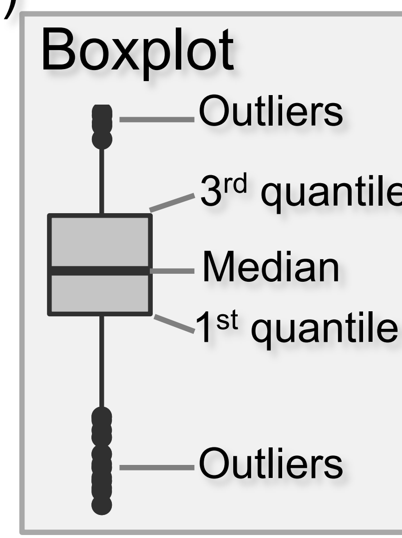
Accuracy (correction rate including chance predictions)



(coldest month)
max(warmest month)

AUC (model performance against chance predictions)

Random

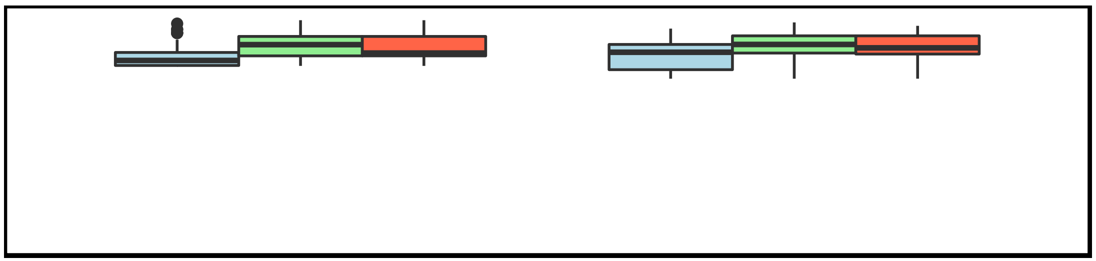


- **Mean SST was better predictor than min and max SST for both species**
- Max/Min SST: principal components score of PCA, substitute for max and min SST to avoid multicollinearity (correlations among variables)

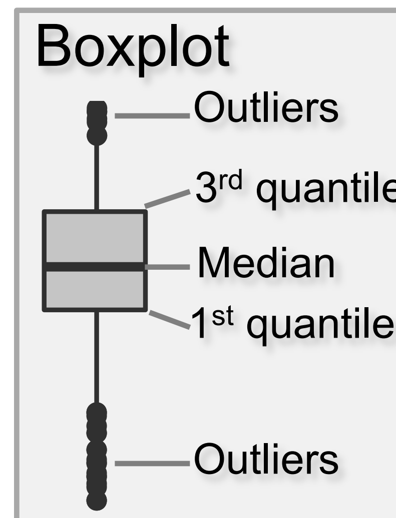
Comparing performances among 3 models

1. SST model: Mean SST, Max/Min SST (warmest/coldest month: score of PCA)
2. SST & Water model: SST indices and water characteristics (Light permeability, chl-*a*)
3. Full variables model: SSTs, Water characteristics, and coastal characteristics (Slope of sea floor, Current exposure, Distance to deep sea, Coastal complexity, Coastal substrate)

Accuracy (correction rate including chance predictions)



AUC (model performance against chance predictions)

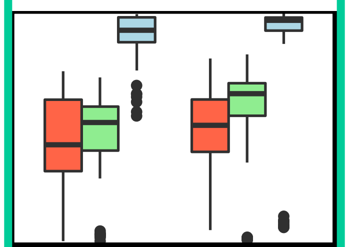


Temperate

Tropical

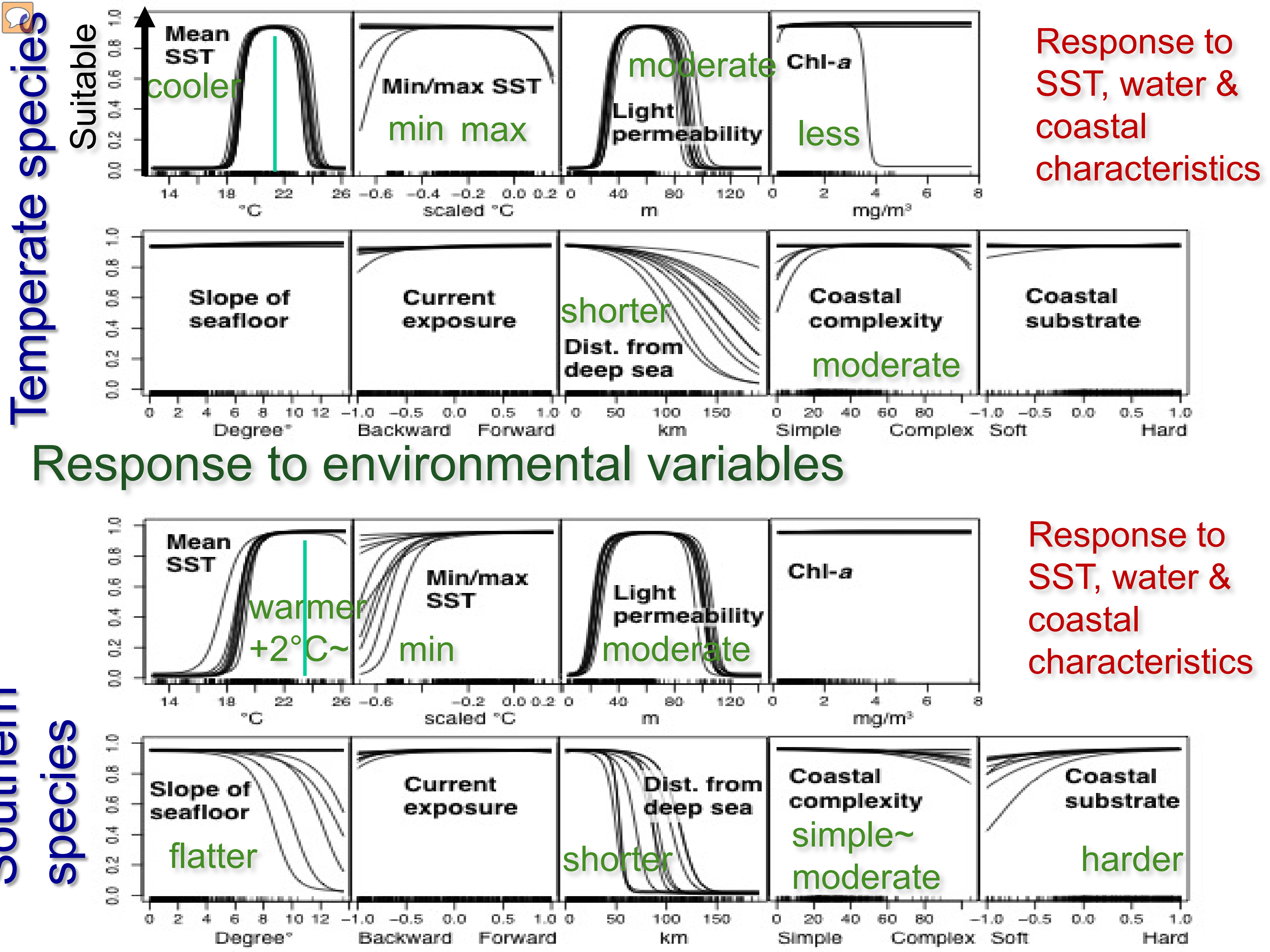
- With adding variables, model performance improved and prediction errors reduced (Full variables model was the best)

Importance for environmental variables



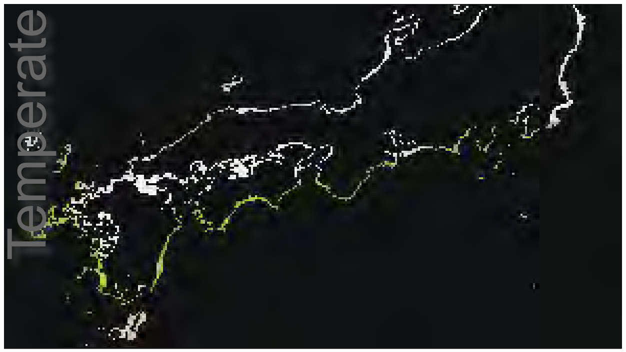
les

- Patterns of variable importances were similar between the species
- 1st: Mean SST; 2nd: Light permeability; 3rd: Dist. Deep sea


Temperate species
Suitable
Mean SST
cooler
°C
Min/max SST
min max
scaled °C
moderate
Light permeability
m
Chl-a
less
mg/m³
Response to SST, water & coastal characteristics
Slope of seafloor
Degree°
Current exposure
Backward Forward
shorter
Dist. from deep sea
km
Coastal complexity
moderate
Simple Complex
Coastal substrate
Soft Hard
Response to environmental variables
Mean SST
warmer
+2°C~
°C
Min/max SST
min
scaled °C
Light permeability
moderate
m
Chl-a
mg/m³
Response to SST, water & coastal characteristics
species
Slope of seafloor
flatter
Degree°
Current exposure
Backward Forward
Dist. from deep sea
shorter
km
Coastal complexity
simple~ moderate
Simple Complex
Coastal substrate
harder
Soft Hard

Prediction: past, current, and near-future (full model)

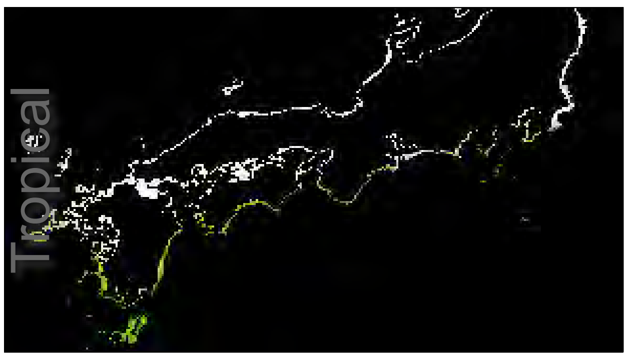
1990s 2010s 2030s



Stable

X X X X

Local extinctions



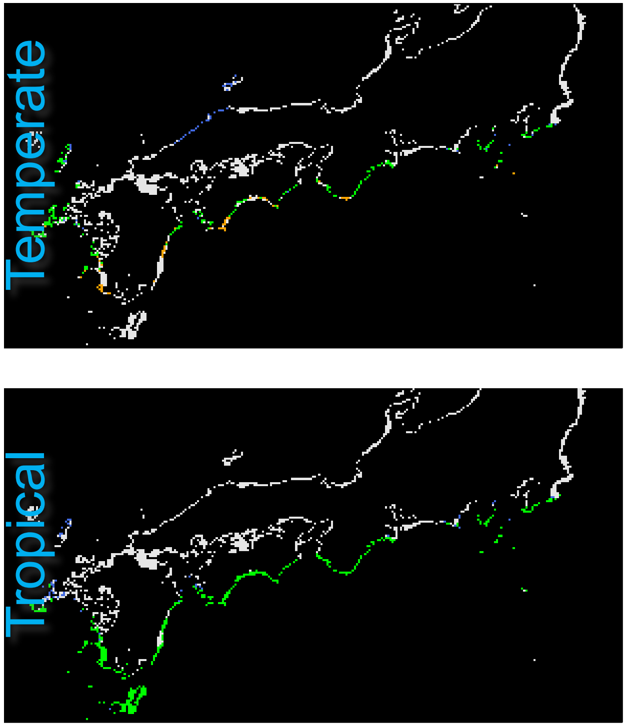
Expansions

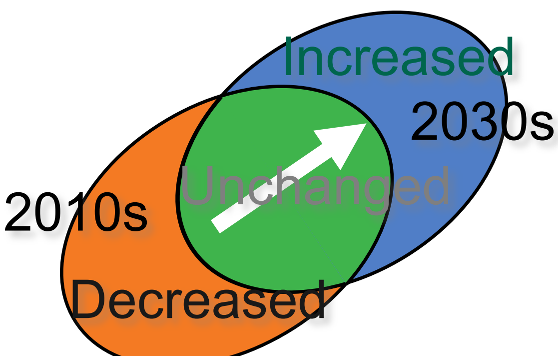
Expansions

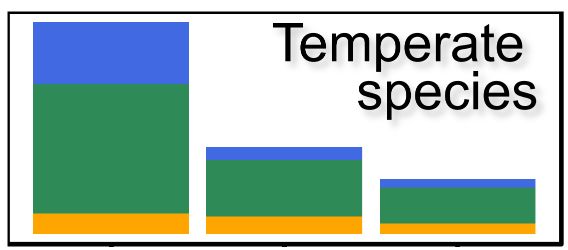
0 probability 1

- Temperate species: habitat contractions around southern edges
- Tropical species: habitat range expanded north-easternward

SST model | SST & Water model | Full variable model







Tropical species

- SST model, SST & Water model overestimated habitable area and habitat changes
- Temperate sp.: Decrease ≈ Increase; Tropical sp.: Decrease << Increase

Summary

- What is the relative importance of temperature and other environmental factors in predicting seaweed distributions?

–> Mean temperature was the main factor, but light permeability and coastal characteristics were also important factors

–> Considering local managements of coastal land uses and terrestrial runoff could improve habitat suitability of seaweeds

- How do the distributions change from current to near-future climates?

–> Temperate species shifted northward with contracting habitable area

–> Southern species shifted northward almost in parallel

The results provide basis for adaptive management of coastal ecosystems to climate change