Sea Surface Temperature (SST) Variabilities in the Oceans

Climate Prediction Division (CPD) / Japan Meteorological Agency (JMA)

Ikuo Yoshikawa
(Senior Coordinator for El Niño Infomation)

TCC Training Seminar, 9:30-10:30, 26, November, 2019

Following the concept of Deser et al. (2010) , *Annu. Rev. Marine. Sci.* doi: 10.1146/annurev-marine-120408-151453

SST Variability: Patterns and Mechanisms

1. Introduction
2. Physical background (ocean vs atmosphere; interaction and feedback system)
3. Datasets; SST and Ocean temperature/salinity
4. Geophysical patterns of non-seasonal sea surface temperature variability
5. Dominant patterns of non-seasonal sea surface temperature variability

    <Tropics>

    (a) the tropical Pacific Ocean - El Niño-Southern Oscillation (ENSO)

    (b) the tropical Indian Ocean - Dipole mode and Basin wide mode

    (c) the tropical Atlantic Ocean – Atlantic Niño and Atlantic meridional modes

    <Extra Tropics>

    (e) the Pacific Decadal Oscillation and IPO / Meridional mode / NPGO – NPO

    (f) the Atlantic Multi-decadal Oscillation and Tripolar / Meridional mode – NAO

6. Relations between the SST variabilities and the Global SST warming

Differences between Ocean and Atmosphere (Troposphere)

Key wards:

role of oceans, density, heat content/capacity, buoyancy, heat source, land and ocean, fresh water, time scales,

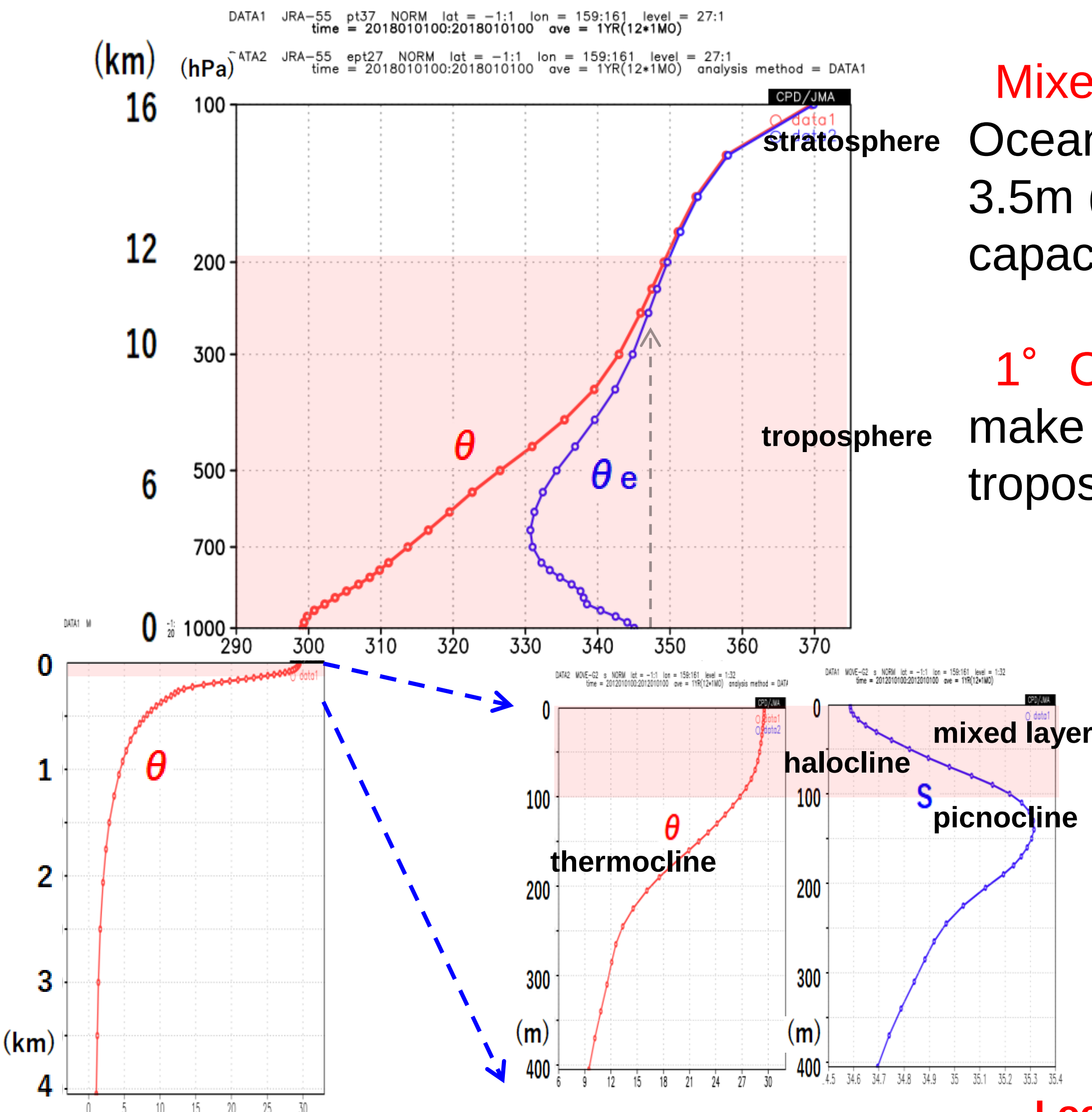
	density (kgm^{-3})	specific heat ($Jkg^{-1}K^{-1}$)	specific heat ($Jm^{-3}K^{-1}$)
Troposphere	1.2	1000	1,200
Ocean	1025	4200	**4,100,000**

	Troposphere	Ocean
Thickness (m) :	12,000	4,000
Heat capacity ($Jm^{-2}K^{-1}$) :	**14,400,000**	16,400,000,000

atmospheric heat capacity / ocean specific heat = 14,400,000/4,100,000 = 3.5m

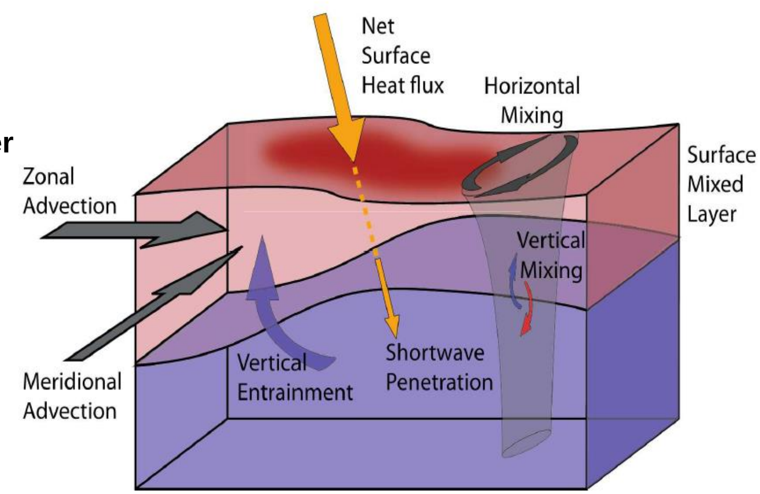
- Ocean has 1,000 times larger heat capacity than atmosphere.
- Heat capacity of troposphere (thickness of 12km) corresponds to 3.5m thick subsurface ocean water.

Structure of annual mean potential temperature (1981-2010 mean) in the western equatorial Pacific (0N, 160W)



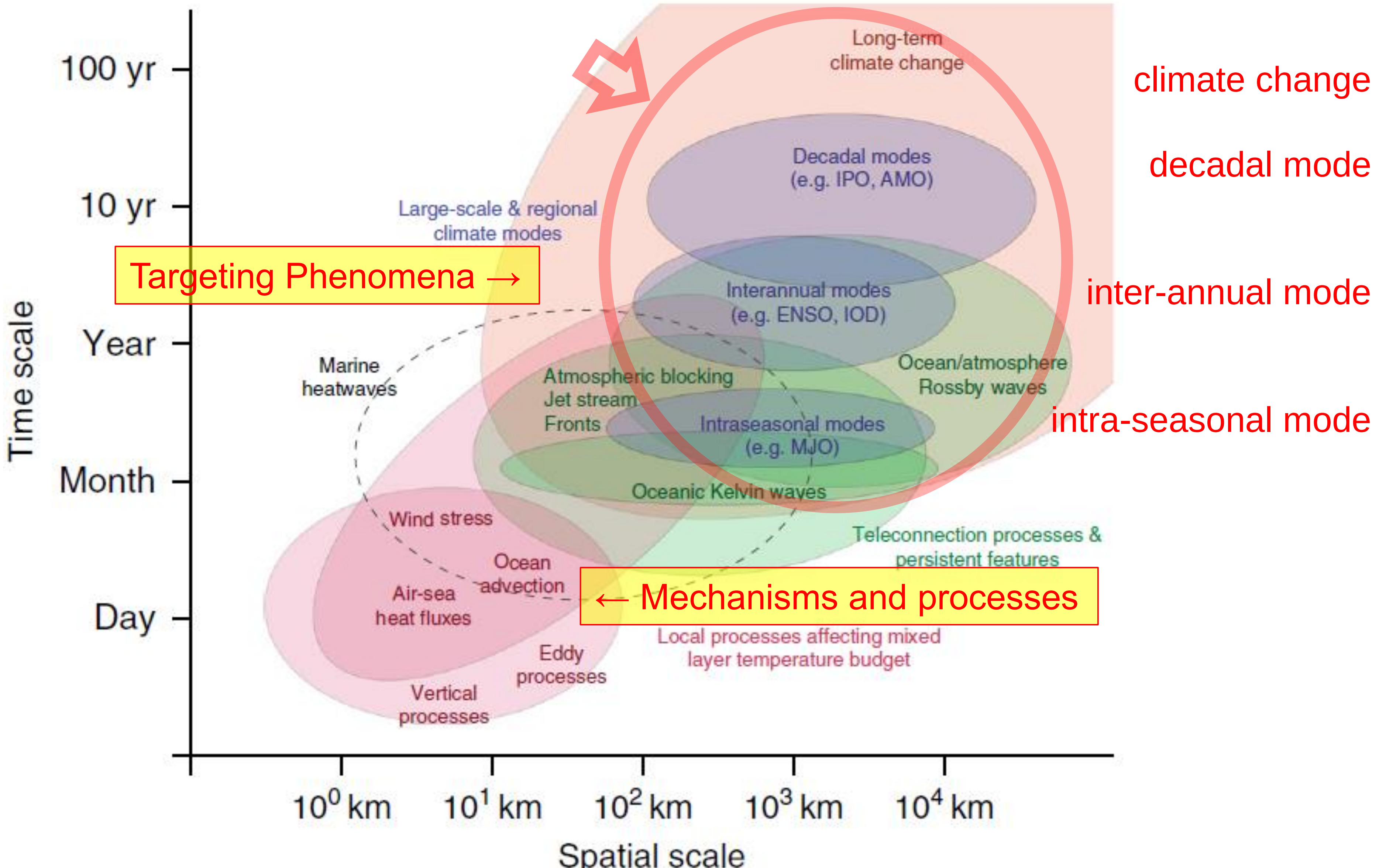
Mixed layer depth in the tropical Pacific Ocean (～100m) is quite deeper than 3.5m (～12km atmospheric heat capacity).

1° C changes in the ocean mixed layer make nearly 30° C changes in the troposphere.



Local processes which can alter surface mixed layer temperature (Holbrook et al. 2019)

Ocean and Atmosphere coupling phenomena

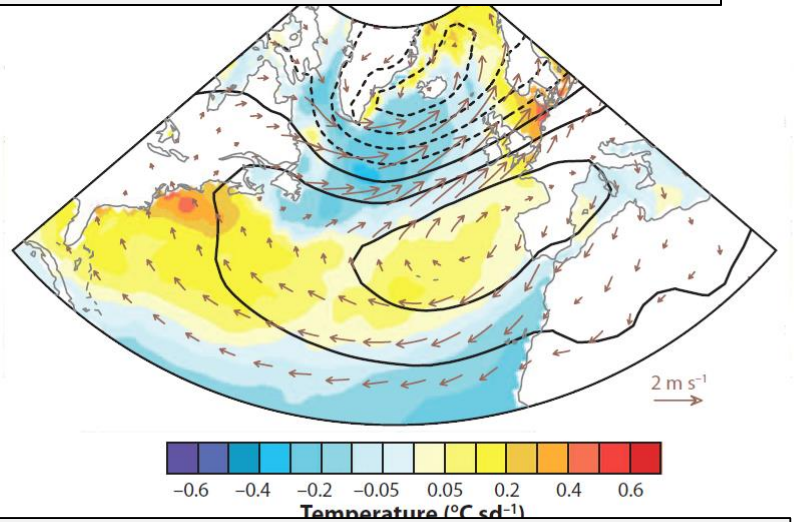


Holbrook et al. 2019

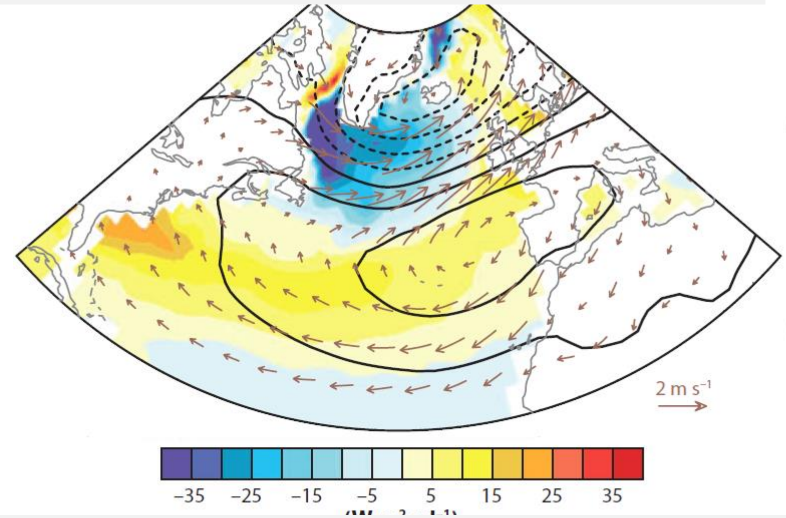
Winter NAO make SSTA pattern

Deser et al. (2010)

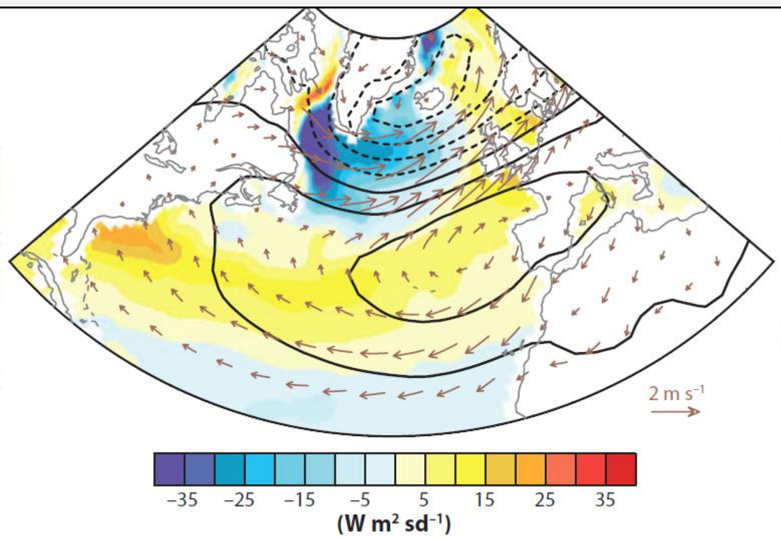
(a) SST: shading, **SLP**: contours, **Surface wind**: arrows



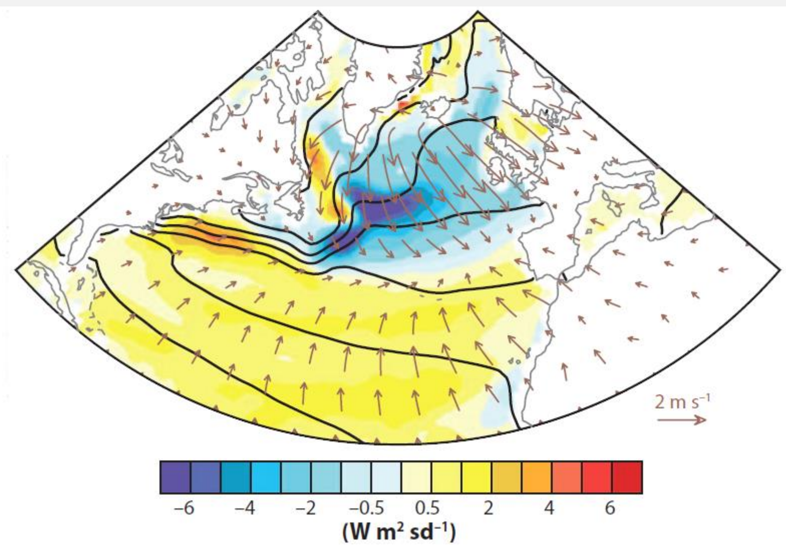
(b) Heat flux: shading, **SLP**: contours, **Surface wind**: arrows



(d) Heat of (b)+(c) : shading, **SLP**: contours, **Surface wind**: arrows



(c) Ekman heat transport: shading, **Norm SST**: contours, Ekman currents: arrows



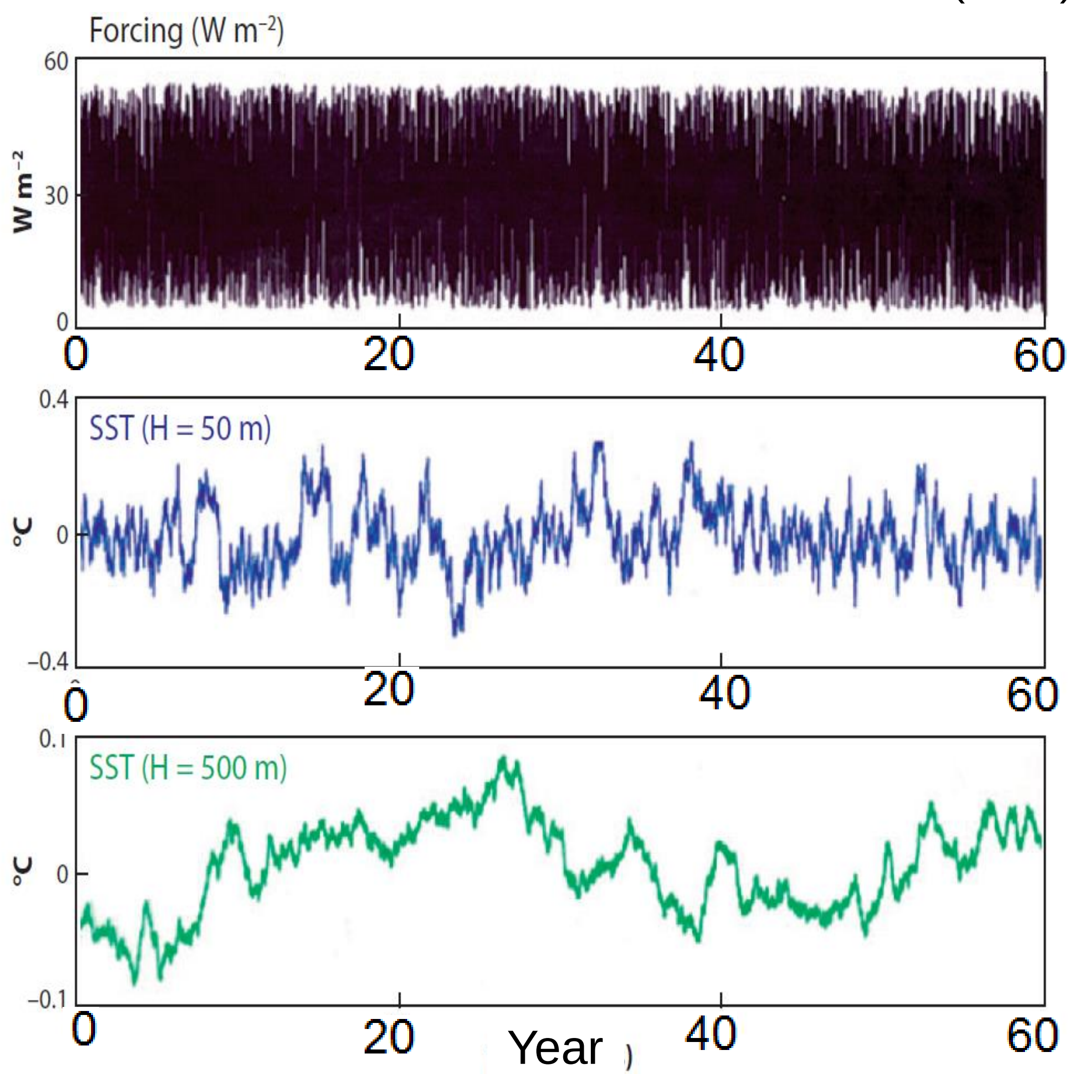
Random atmospheric forcing and Response of upper ocean

Deser et al (2010)

a random - “white noise”- **atmospheric heat flux forcing** time series

upper-ocean mixed-layer temperature response for a **mixed-layer depth of 75 m**

upper-ocean mixed-layer temperature response for a **mixed-layer depth of 500 m**



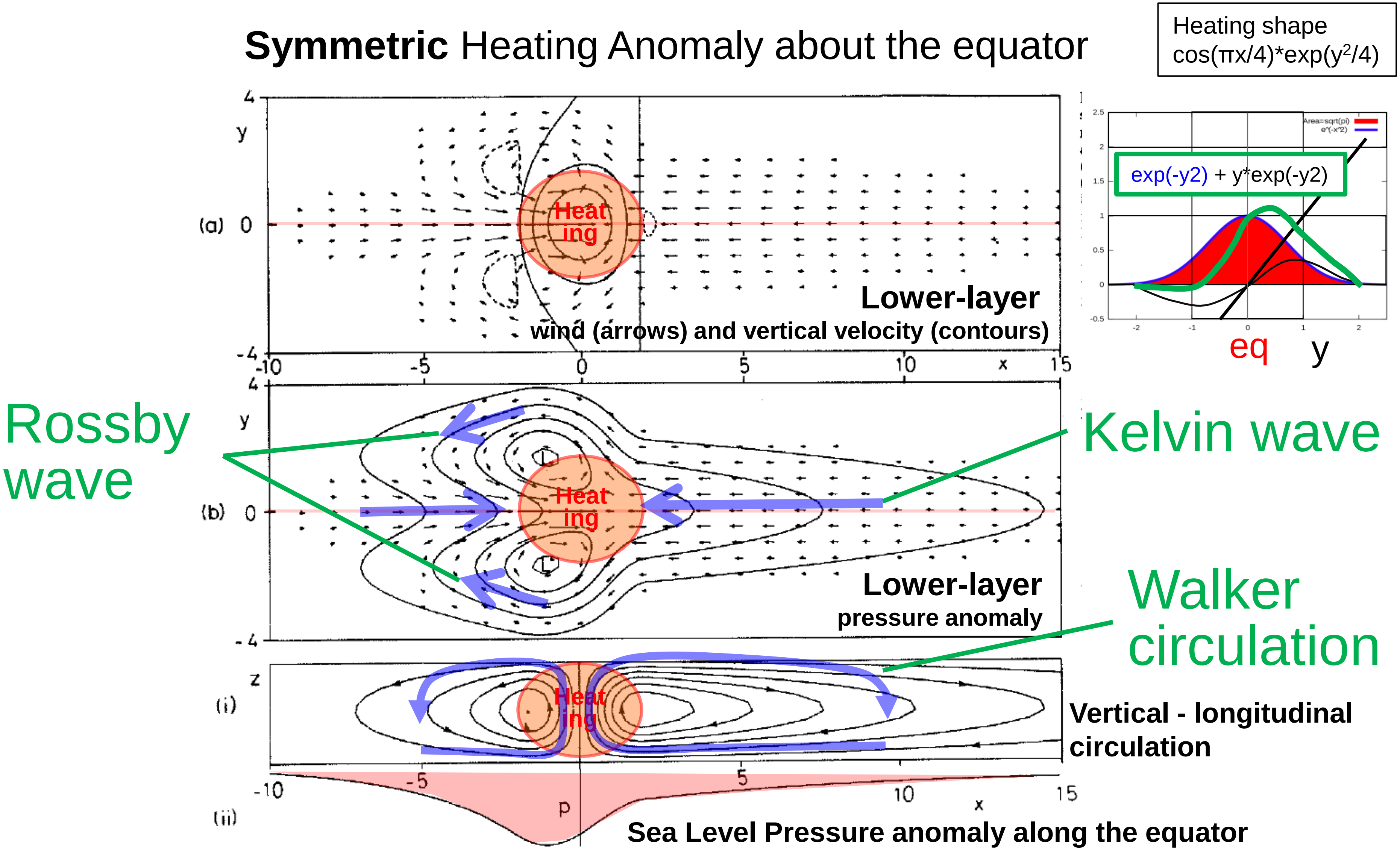
Note the very slow fluctuations in the ocean mixed-layer temperature response.

Interaction / feedback mechanisms between Ocean and Atmosphere

Key wards:

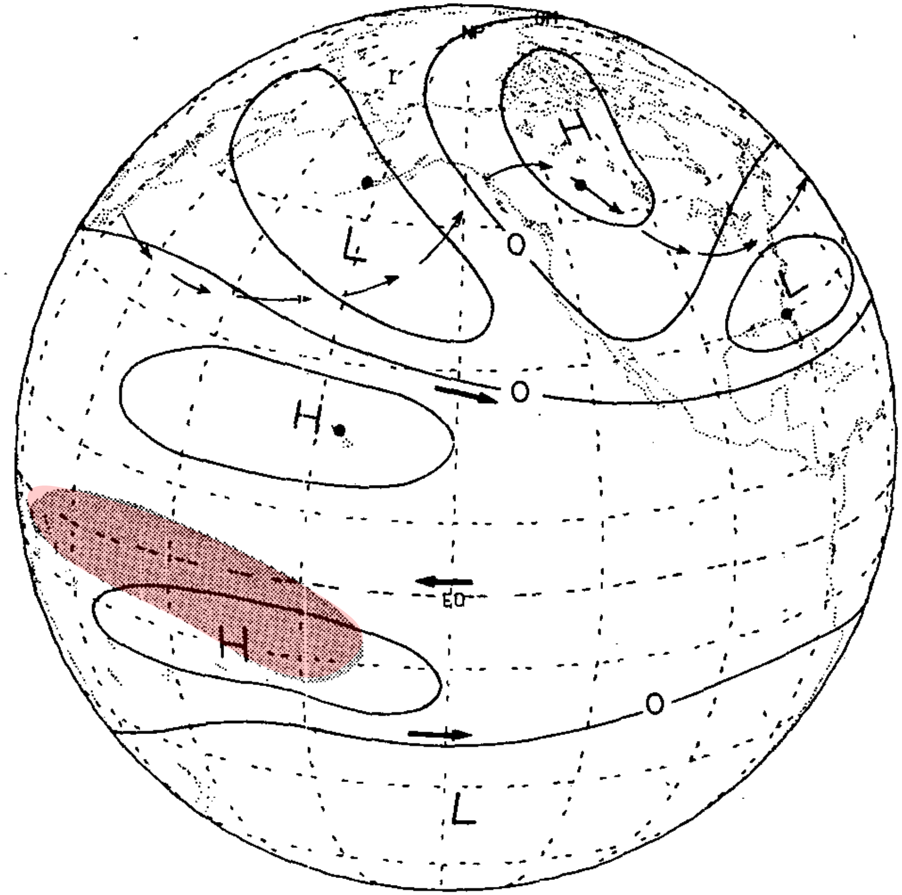
SST, wind, evaporation, thermocline, advection, upwelling, Ekman transport, atmospheric convection, air temperature and sea level pressure , Walker circulation, Rossby wave, Kelvin wave, mixed layer depth, teleconnection, etc.

Heat-induced tropical circulation (Gill 1980)

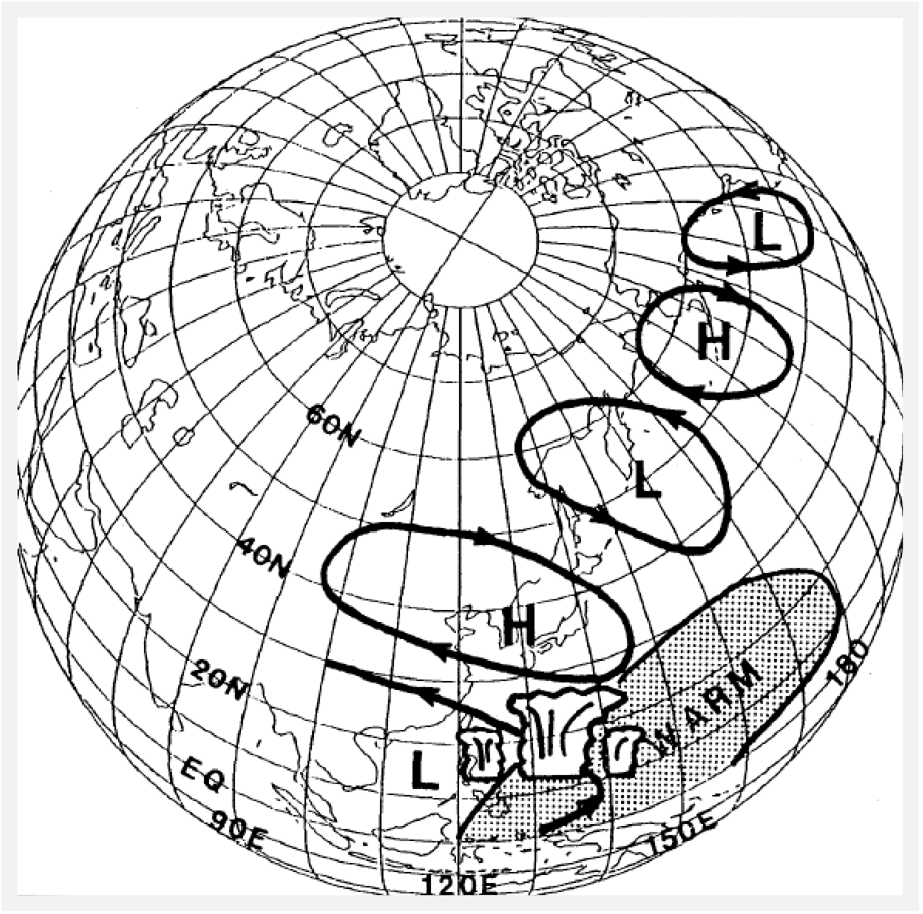


Atmospheric response to SST anomalies

Pacific North American (PNA) pattern
Horel and Wallace (1981)



Pacific Japan (PJ) pattern
Nitta (1987)



Unstable and damped equatorial modes

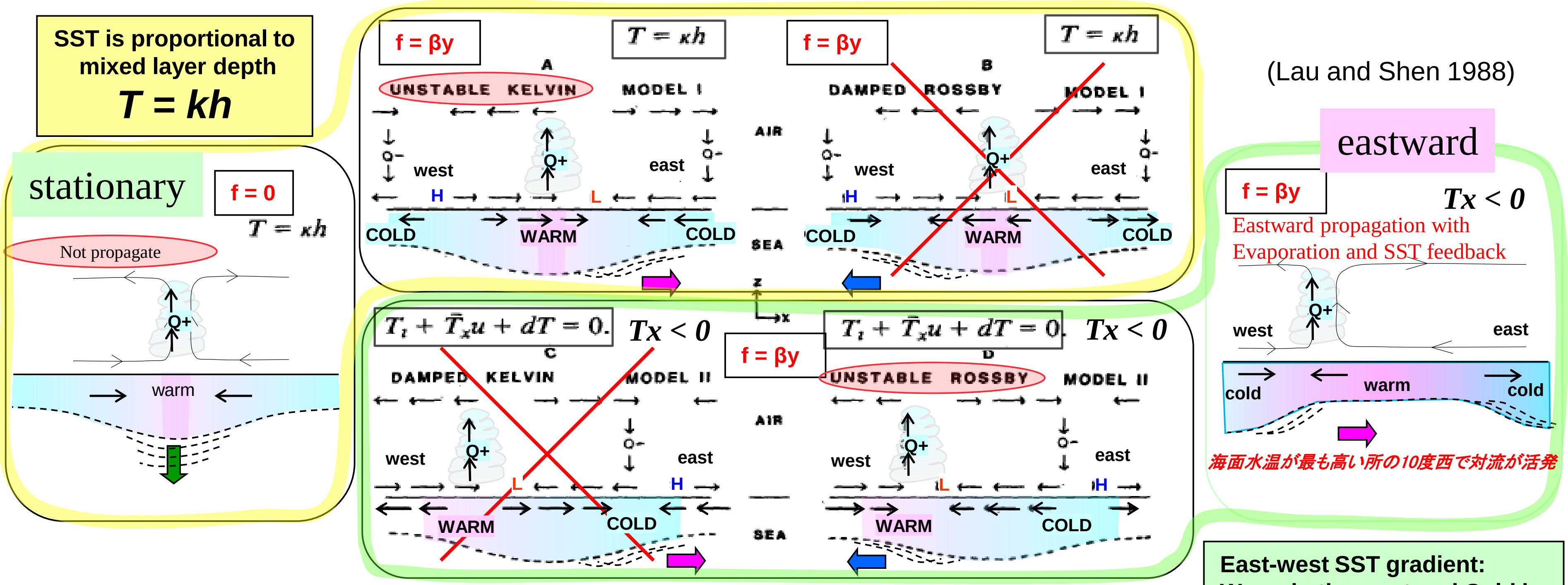
Yamagata (1986), Hirst (1986)

During weak easterly and weak east-west SST gradient

Eastward propagation

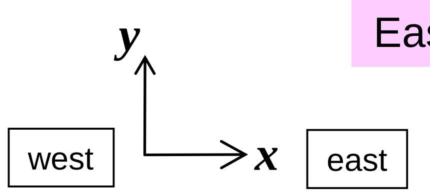
Westward propagation

(Lau and Shen 1988)



Eastward Kelvin wave

Westward Rossby wave



East-west SST gradient: Warm in the west and Cold in the east. SST varies with zonal advection.

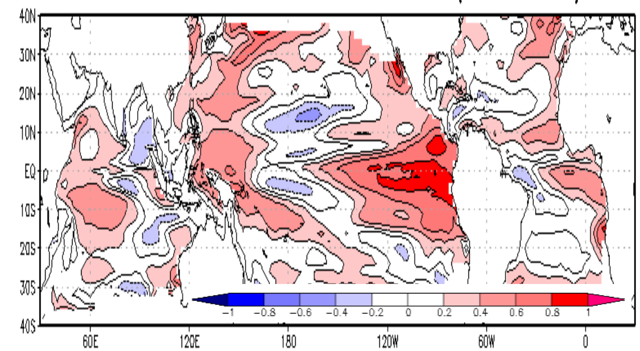
Tx < 0

During strong easterly and strong east-west SST gradient

Unstable ocean and atmosphere interactions

a) Stationary mode (f=0)
   SST is proportional to thermocline depth (convergence ∞ thickness of subsurface)
b) Unstable oceanic Kelvin wave : eastward moving mode (f=βy)
   SST is proportional to thermocline depth (convergence ∞ thickness of subsurface)
c) Westward ocean temperature gradient : westward moving mode
   SST varies with advection
d) Evaporation and SST feedback : eastward moving mode

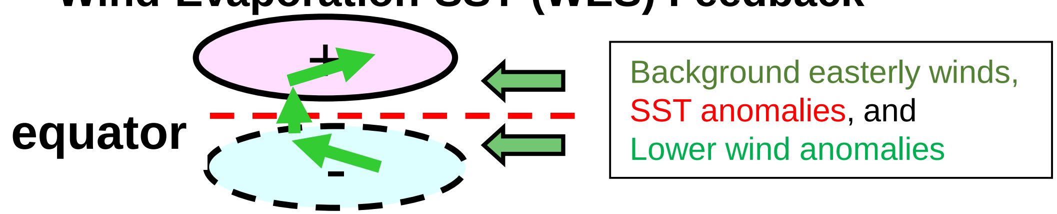
Correlation of SST and D20 in ODAS (1981-2000)



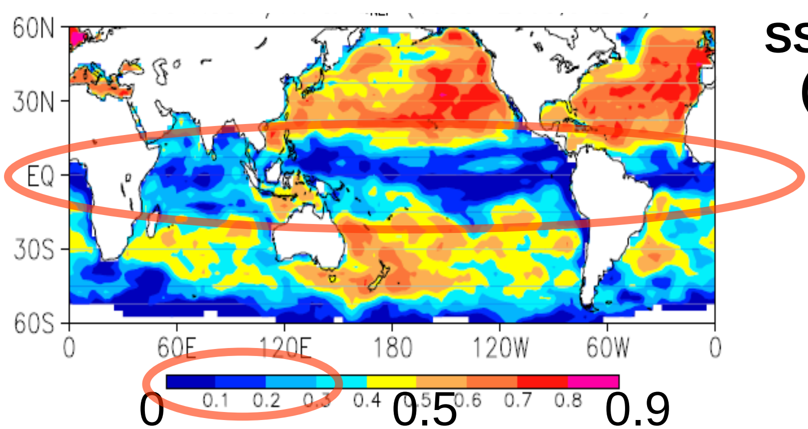
Mechanism leading to large scale unstable moist air convection

a) Evaporation – SST feedback
b) Evaporation – Wind feedback
c) Condensation – convergence feedback

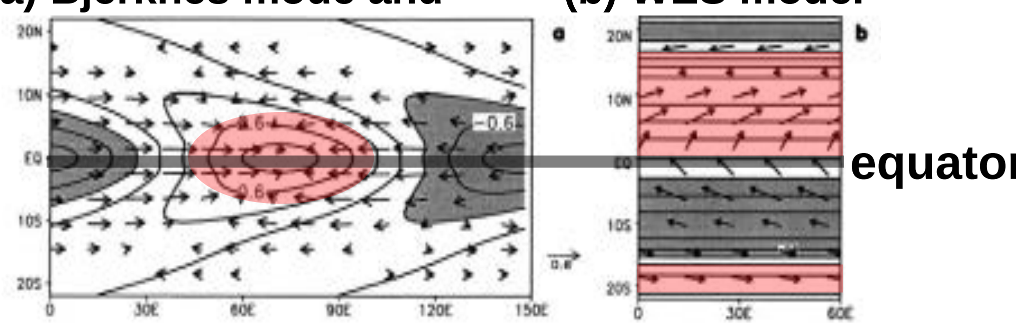
(a) + (b) +(c) ➔ ➔ ➔ ➔ ➔ ➔ Wind-Evaporation-SST (WES) Feedback



Anomaly correlation between **rate of SST anomaly chages** and **net heat flux** (October – February in 1980-2005)



SST and wind anomaly distributions : Xie et al. (1999)
(a) Bjerknes mode and (b) WES mode.



Datasets

SST and

Subsurface Temperature/Salinity

SST datasets – COBE-SST (iTacs data)

(Centennial in situ Observation-Based Estimates of the variability of SSTs and marine meteorological variables) – take pronunciation from ' KOBE collection'

This analysis utilize only in-situ maritime ocean observations to monitor the long term historical SST variations. COBE-SST is also utilized as an boundary condition of JRA-55 Atmosphere model.

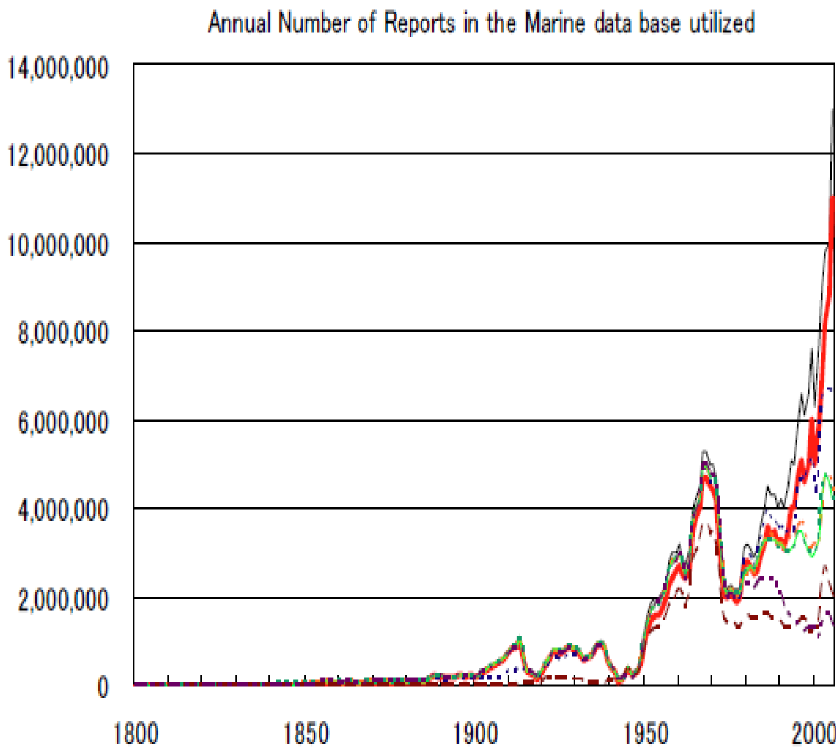
Available analyzed period : 1890 – present, monthly (TCC), monthly/daily (iTacs)

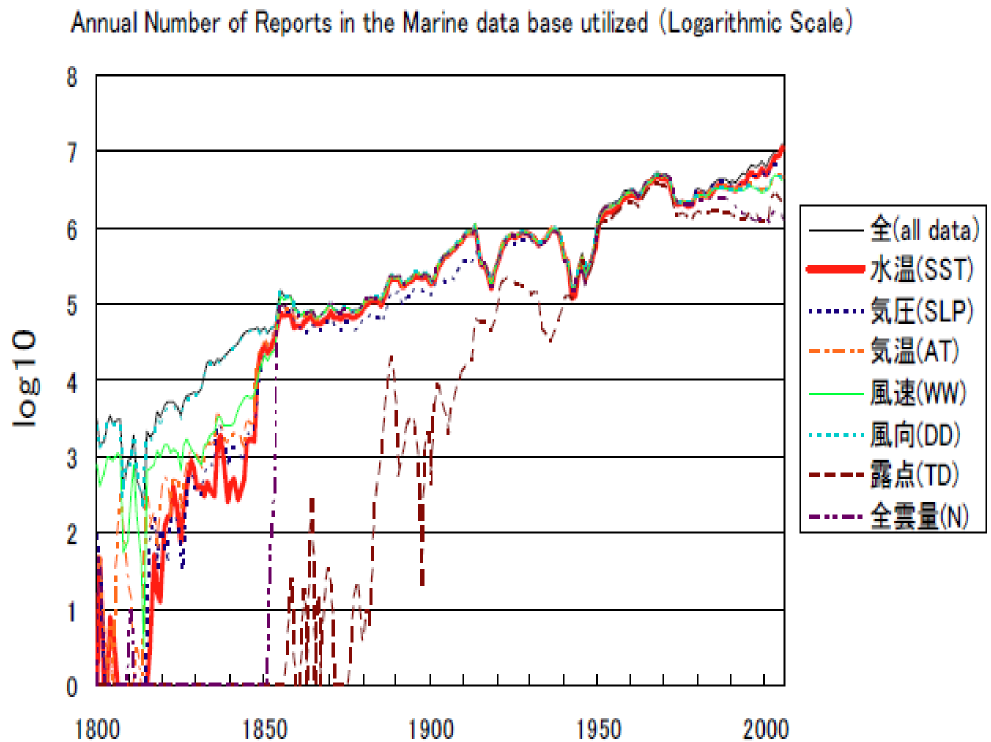
Resolution : 1.0 degree longitude x 1.0 degree latitude (360 x 180 grids)
longitude grid from 0.5 degree to 359.5 degree
latitude grid from -89.5 degree to 89.5 degree

The Characteristics of the Global Sea Surface Temperature Data (COBE-SST) are available in the following address on the TCC Web.

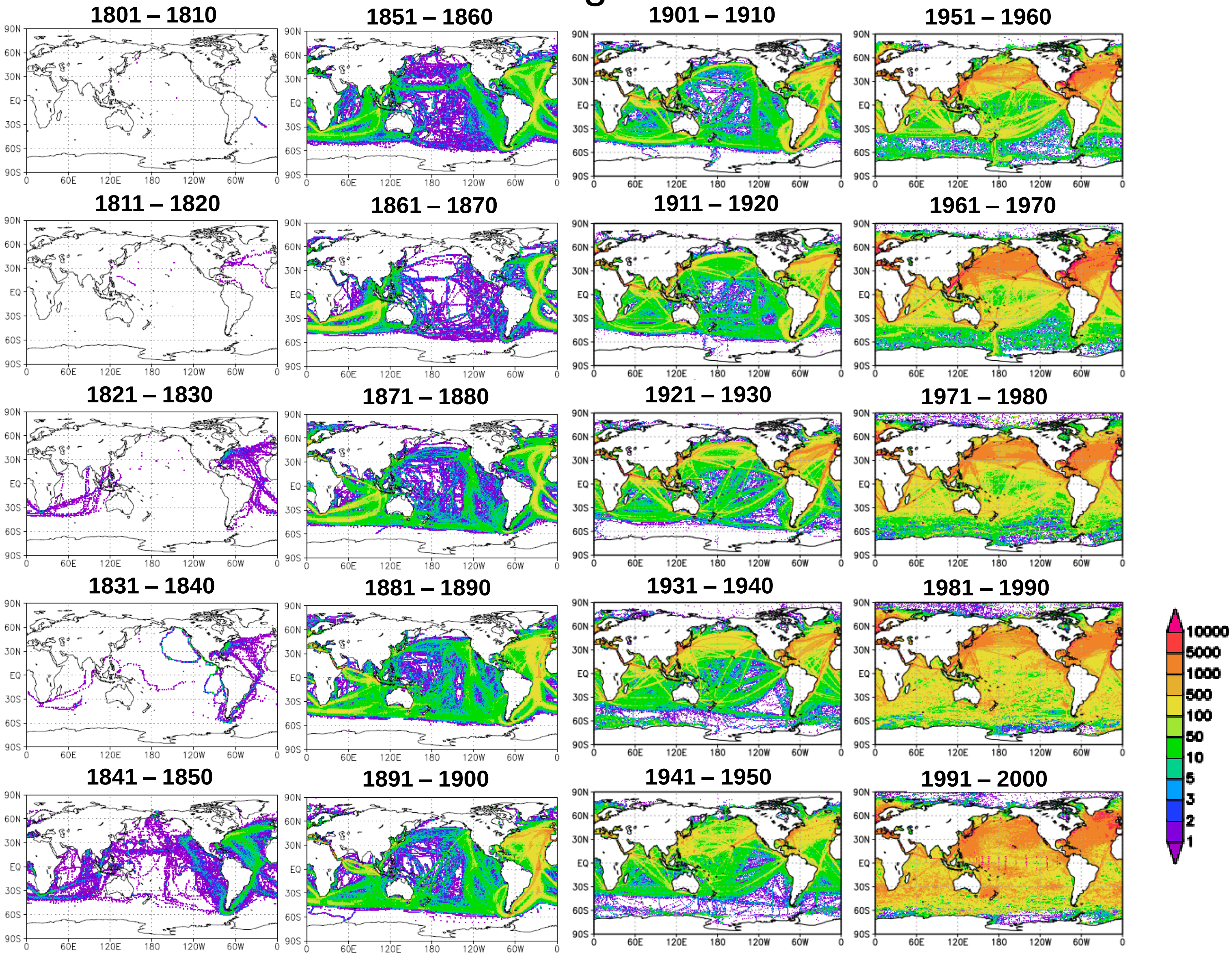
http://ds.data.jma.go.jp/tcc/tcc/library/MRCS_SV12/index_e.htm

The number of SST observation reports in a year

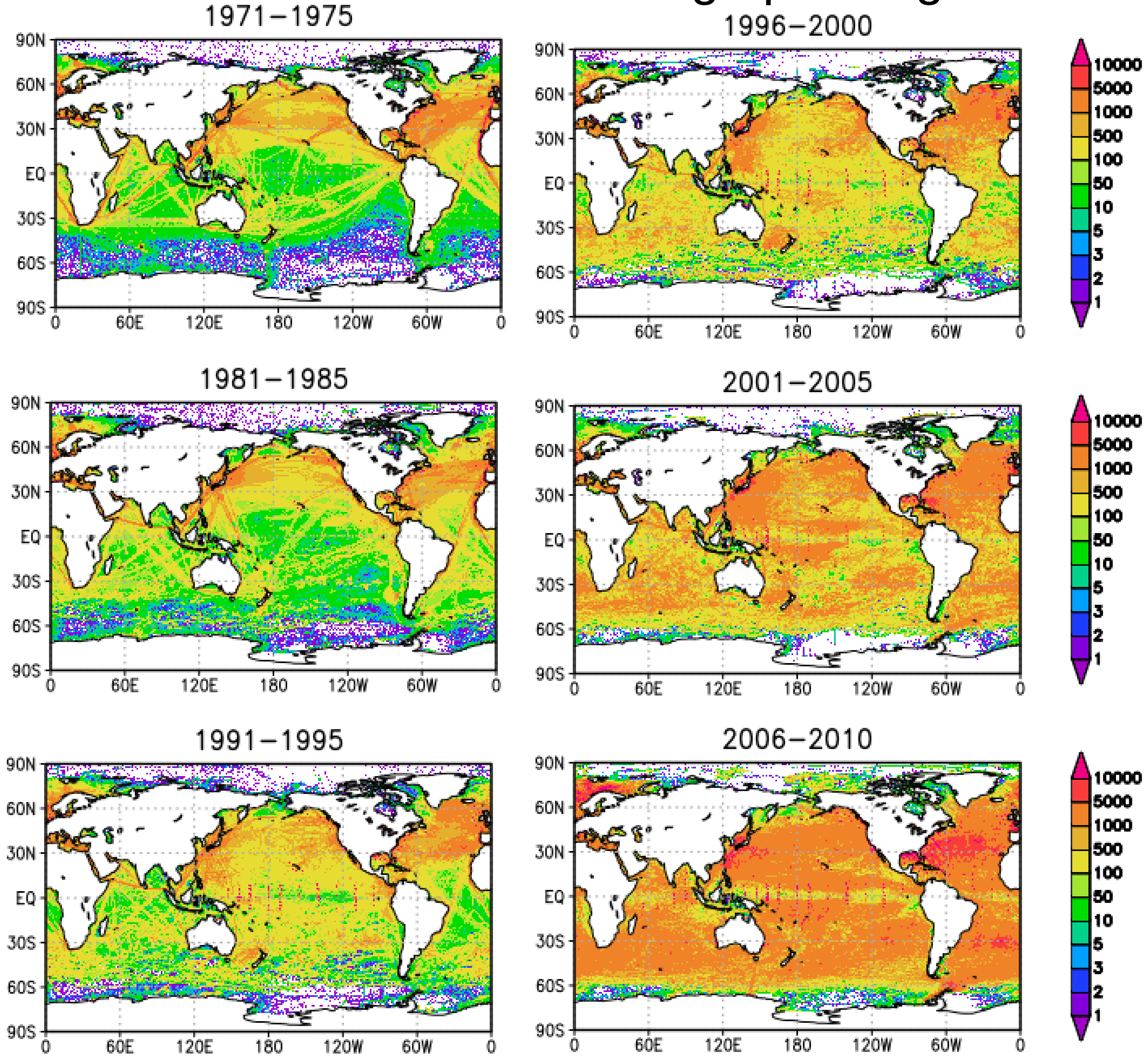




Maritime Meteorological Observations



Recent Observations – Argo profiling floats



Ocean temperature and salinity data - MOVE-G2 (iTacs data)

(Multivariate Ocean Variational Estimation - Global version 2)

Ocean data assimilation system is forced by JRA-55 atmospheric forcing and assimilates COBE-SST, temperature/salinity data observed with Argo profiling float etc. and sea surface height observation with satellites etc.

Available analyzed period : 1958 – present, monthly/daily (iTacs)

Resolution : 1.0 degree longitude x 0.5 degree latitude,

except for the 15ºS - 15ºN band.

ts longitude grid from 0.0 degree to 359.0 degree

ts latitude grid from -5.7 to 5.7 with 0.3 degree interval

from 15.5 to 78.0 with 0.5 degree

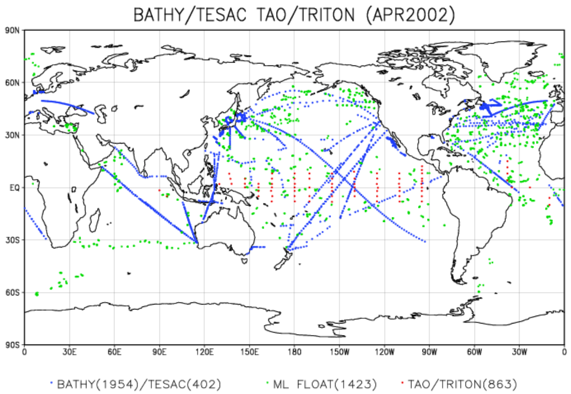
uv longitude and latitude grids are sandwiched ts grids

Some description of MOVE/MRI.COM-G2 are available in the following address on the TCC Web.

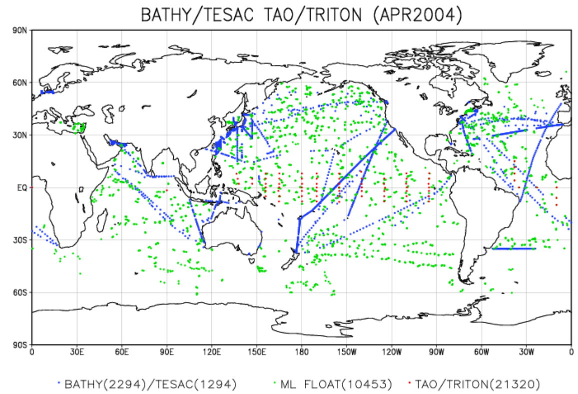
http://ds.data.jma.go.jp/tcc/tcc/products/elnino/move_mricom-g2_doc.html

Historical data distribution of ocean subsurface observation

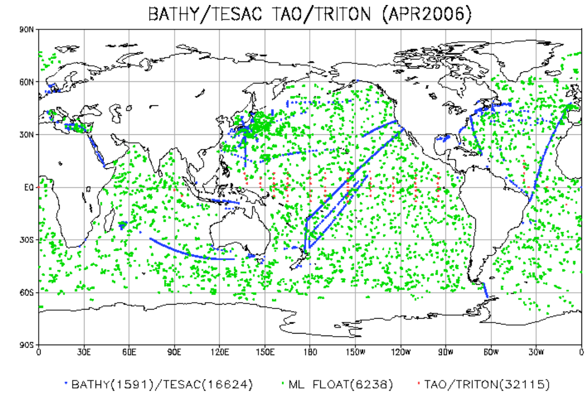
2002



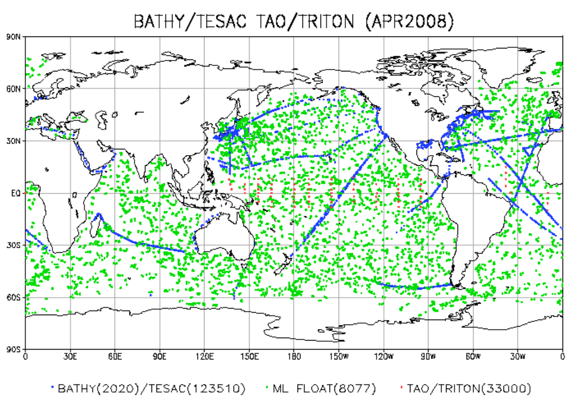
2004



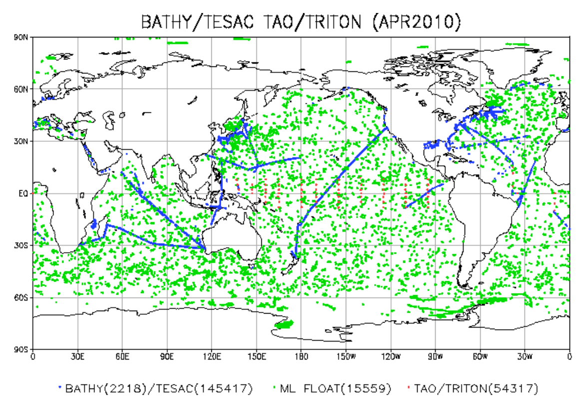
2006



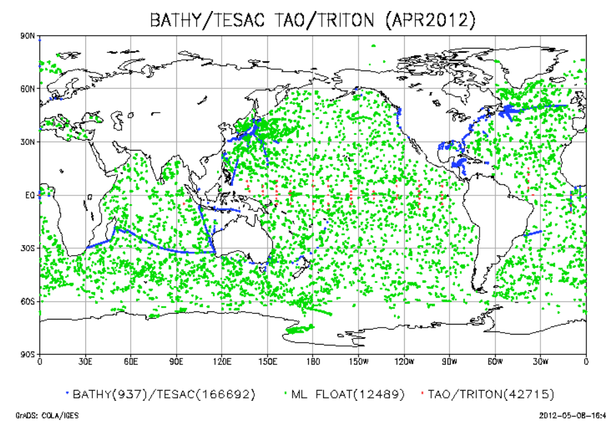
2008



2010

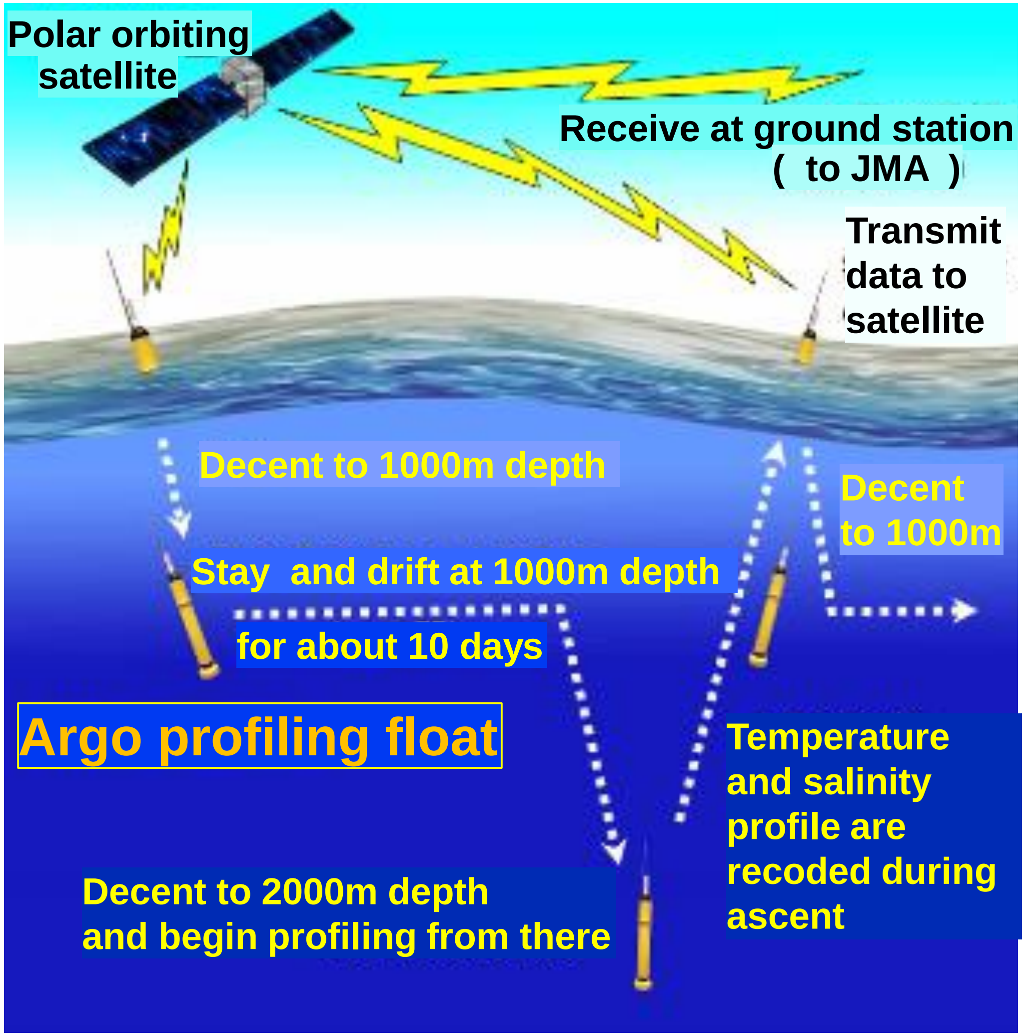


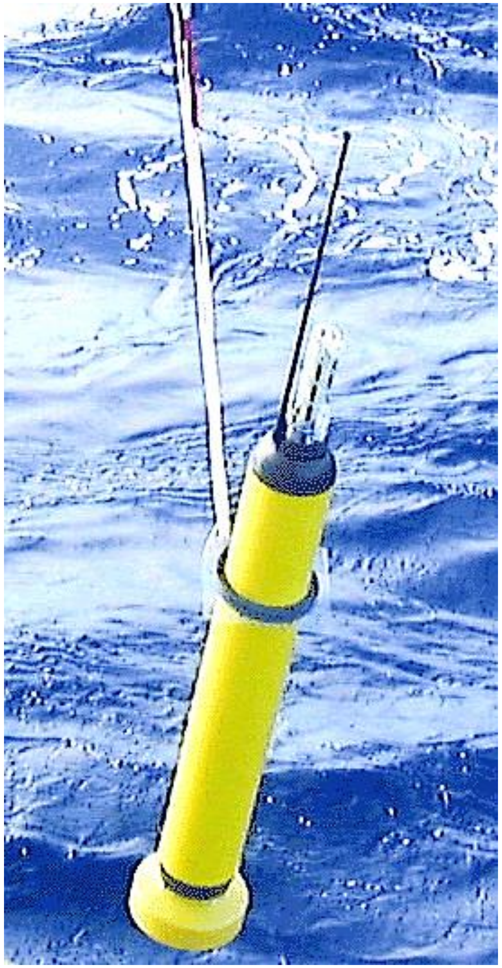
2012



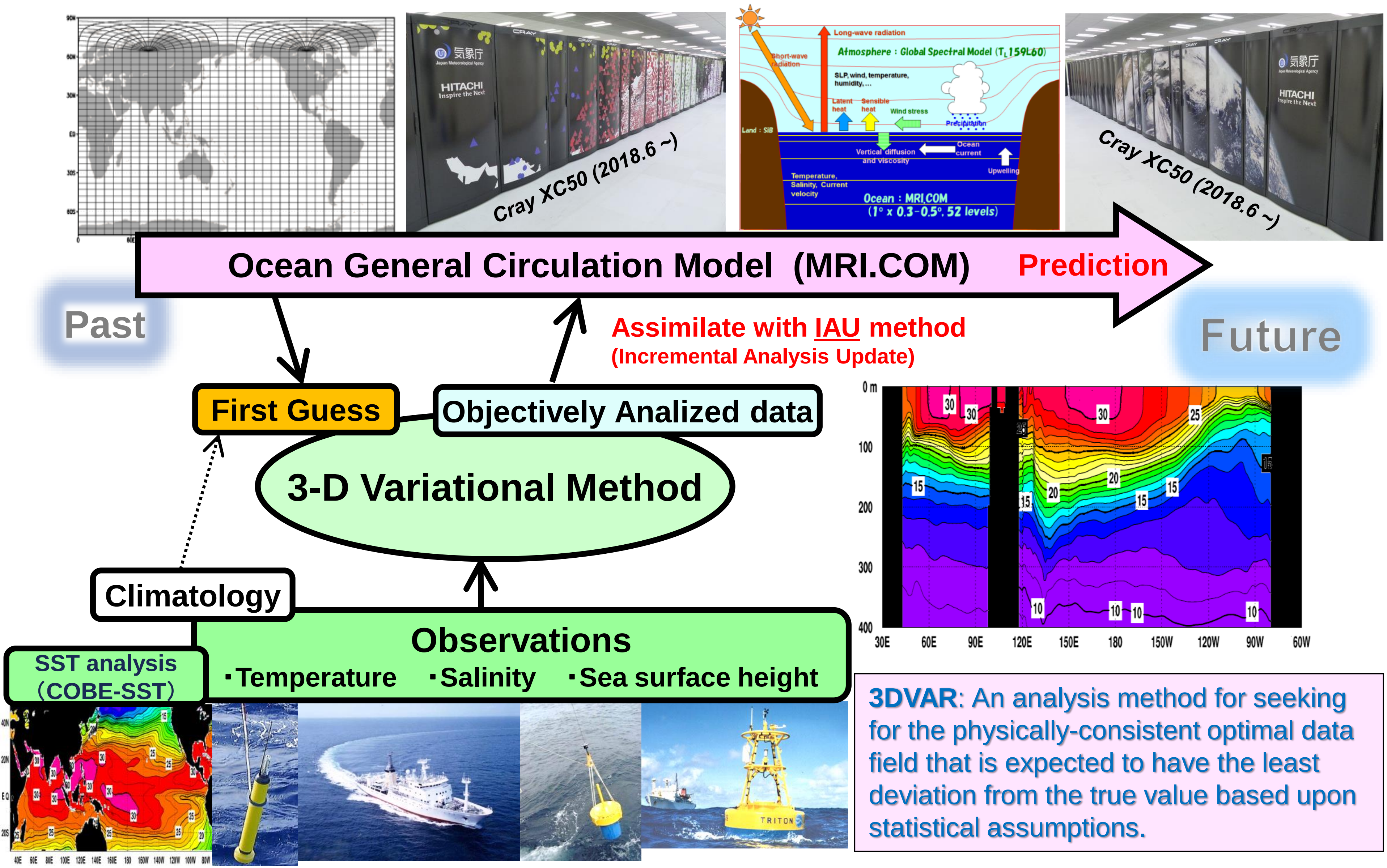
Recently, Argo profiling floats compose the most important and major ocean subsurface observational system.

Argo profiling float





Ocean Data Assimilation System: MOVE-G2

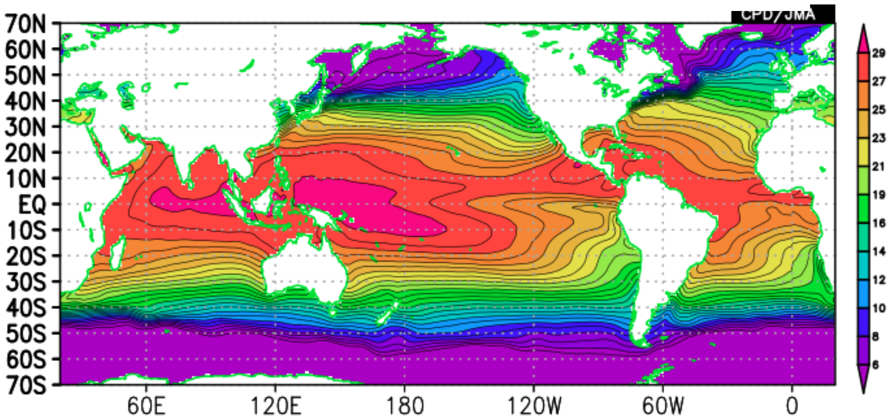


3DVAR: An analysis method for seeking for the physically-consistent optimal data field that is expected to have the least deviation from the true value based upon statistical assumptions.

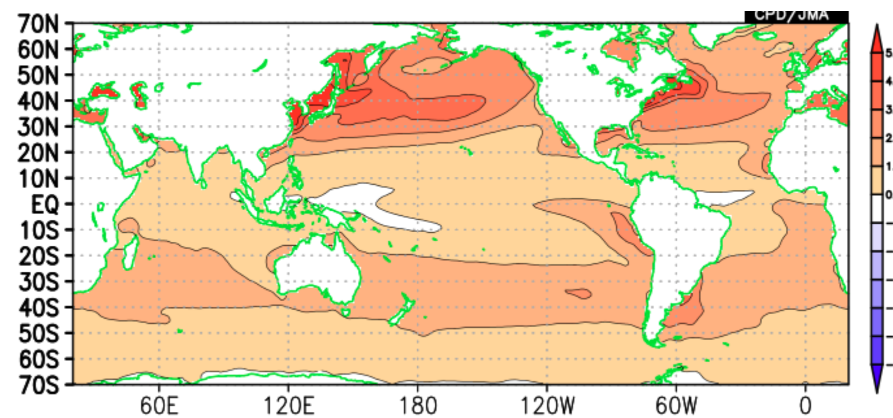
Geophysical patterns of SST variabilities

Geophysical patterns of SST variabilities (1981.1 – 2018.12)

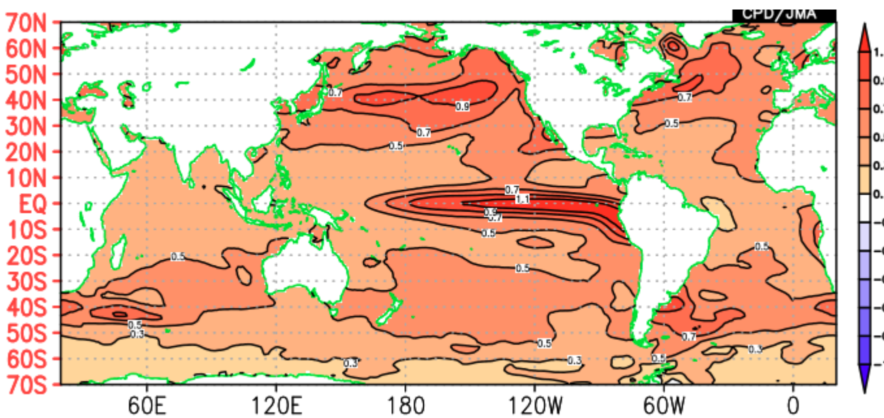
38 year annual average



Standard deviation of SST (seasonal cycle)

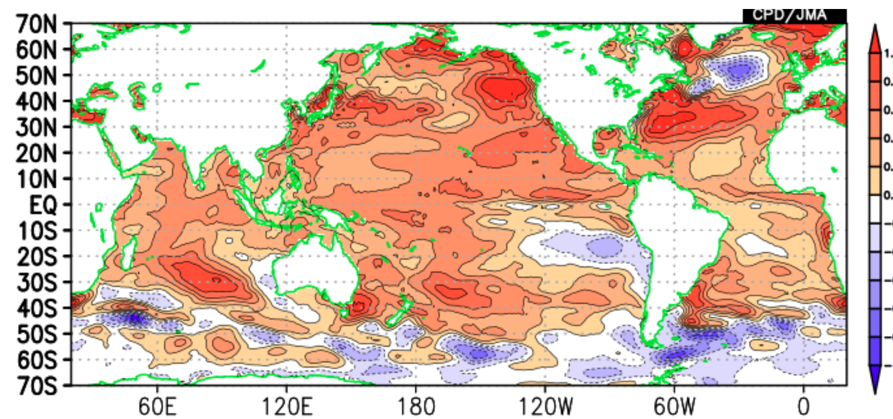


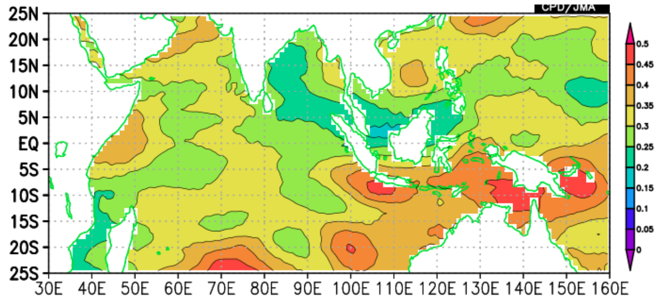
Standard deviation of SST anomalies



Trend ?

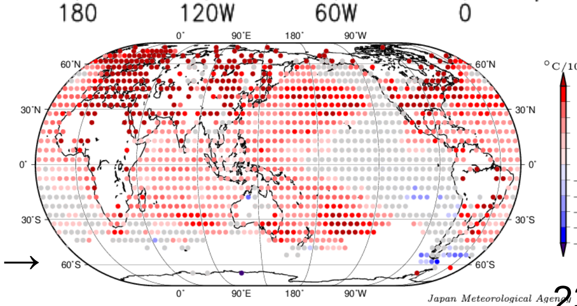
(2014_2018 mean) minus (1981_1985 mean)





←Standard deviation of SST anomalies Indian ocean summer (Jun to November)

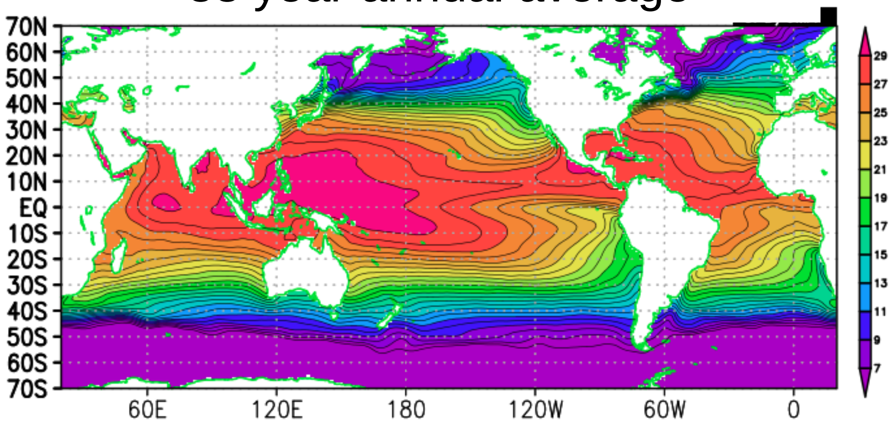
1979-2018 trend→



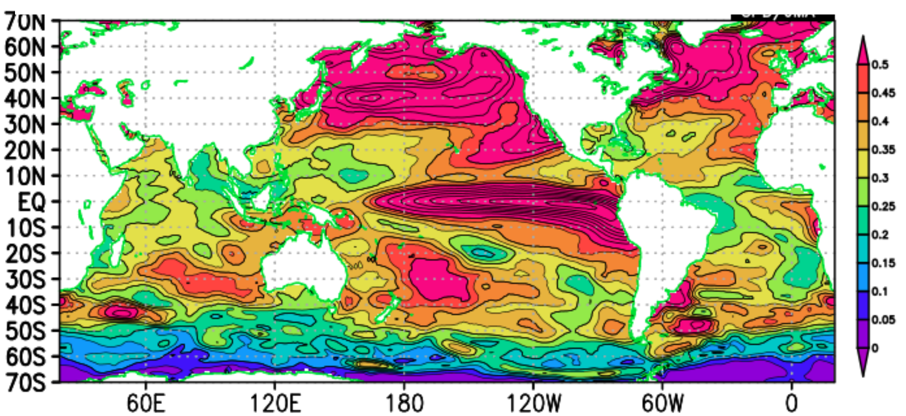
Geophysical patterns of SST variabilities (1981.1 – 2018.12)

Northern Hemisphere
summer – autumn
(June – November)

38 year annual average

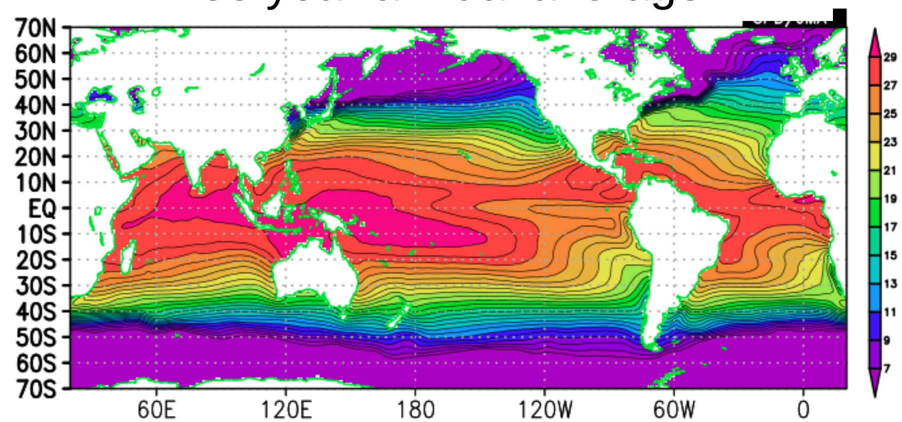


Standard deviation of SST anomalies

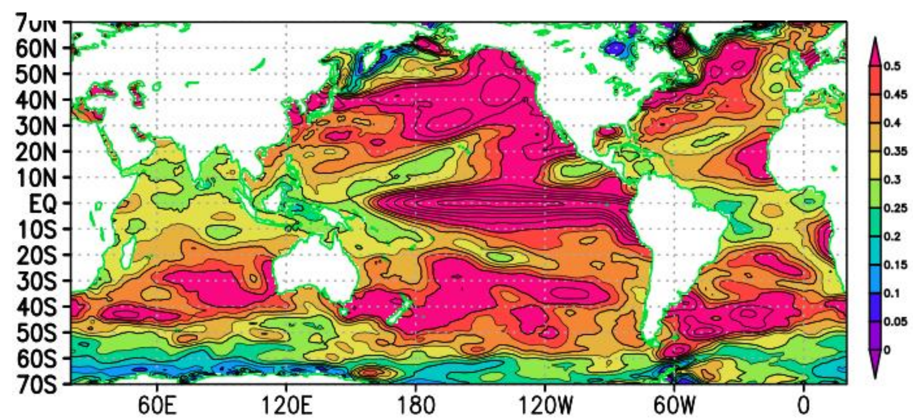


Northern Hemisphere
winter – spring
(December – April)

38 year annual average



Standard deviation of SST anomalies



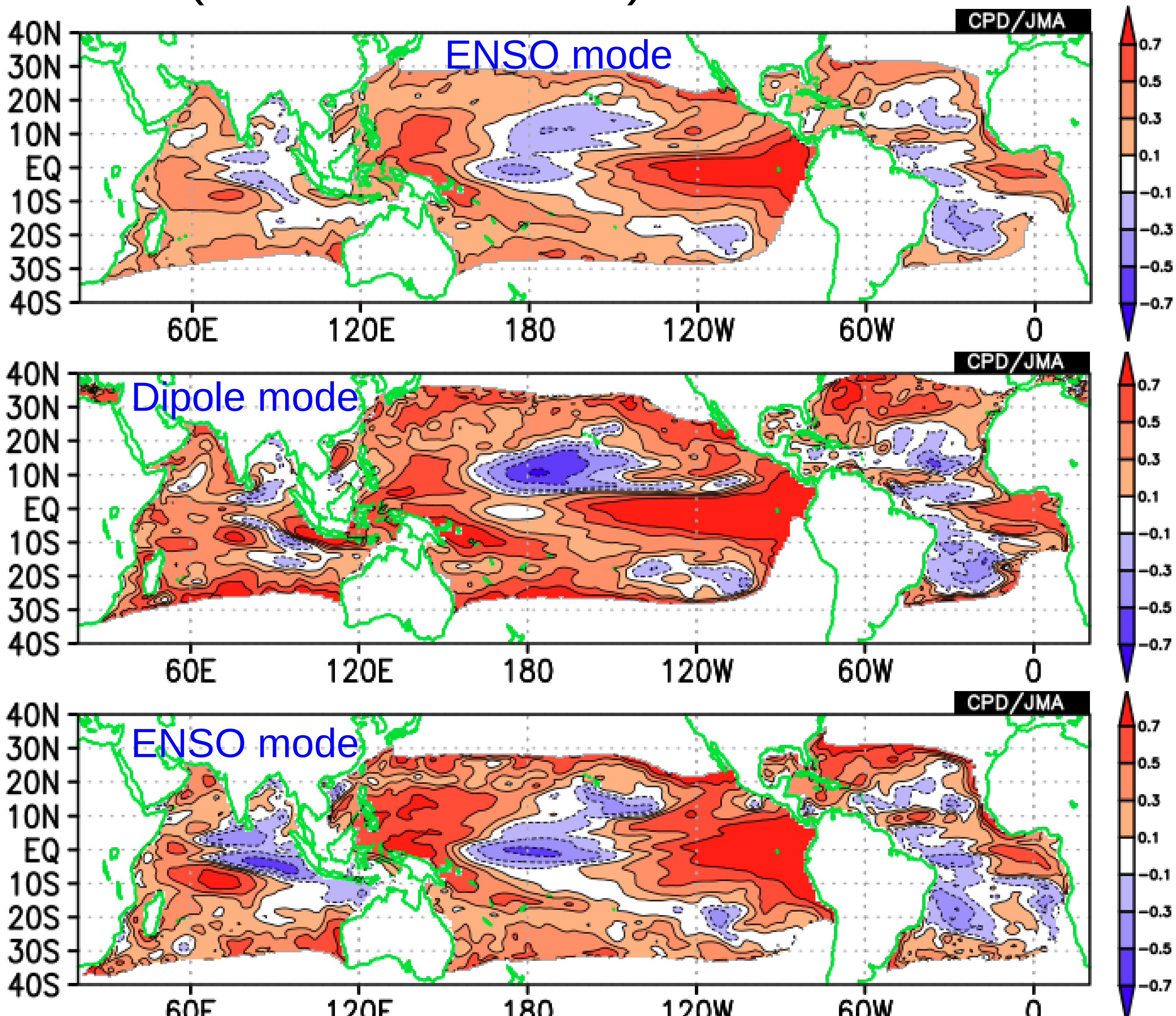
Winter mixed layers are substantially deeper in the subpolar ocean, which reduces the amplitude of the SST response

Correlations between SST and Thermocline Depth (D20) (1981.1 – 2018.12)

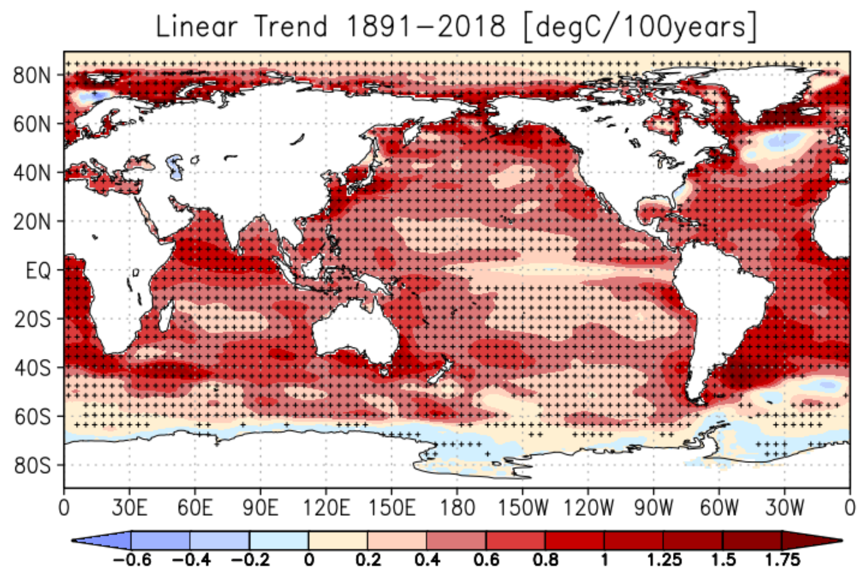
Monthly

Northern Hemisphere
summer – autumn
(June to November)

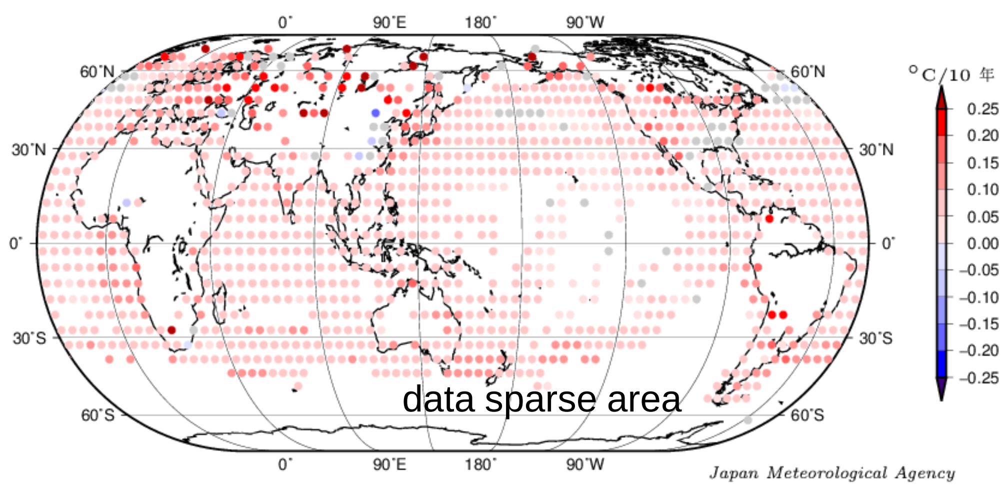
Northern Hemisphere
winter – spring
(December to May)



Long term trends of annual SST
(℃/100 years)

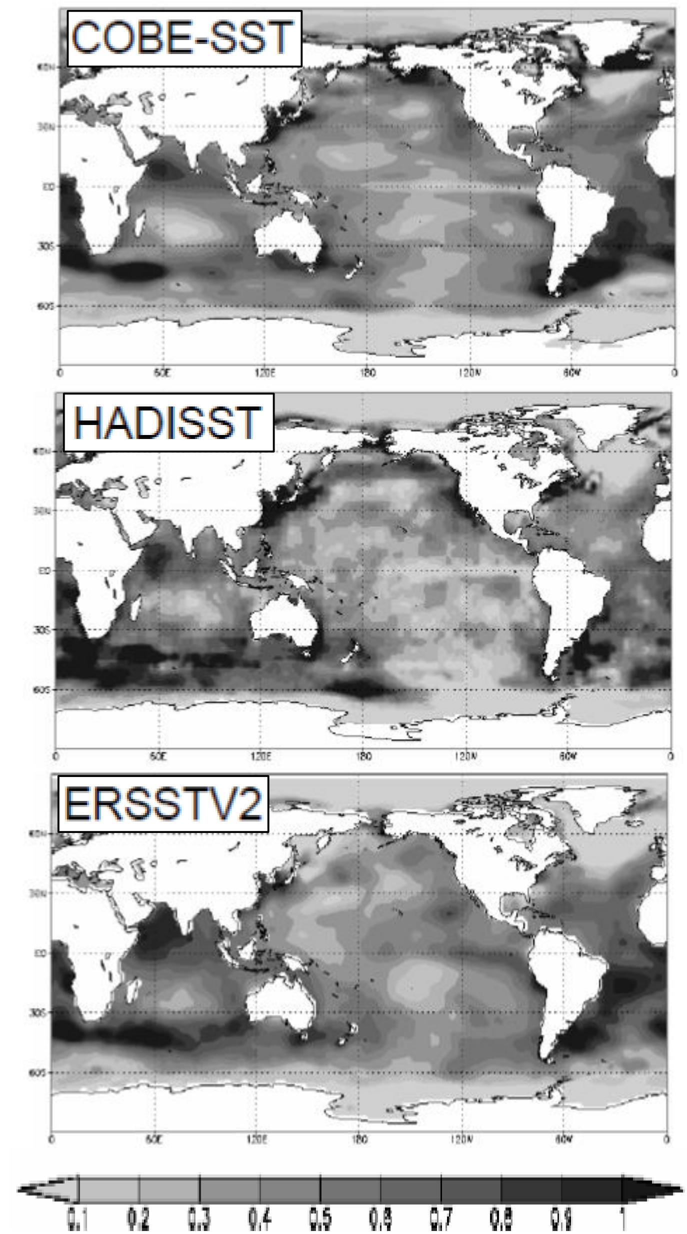


年平均気温長期変化傾向　1891-2018 年



図中の丸印は、5° x 5° 格子で平均した 1891-2018 年の長期変化傾向（10 年あたり）を示す。
灰色は、信頼度 90 %で統計的に有意でない格子を示す。

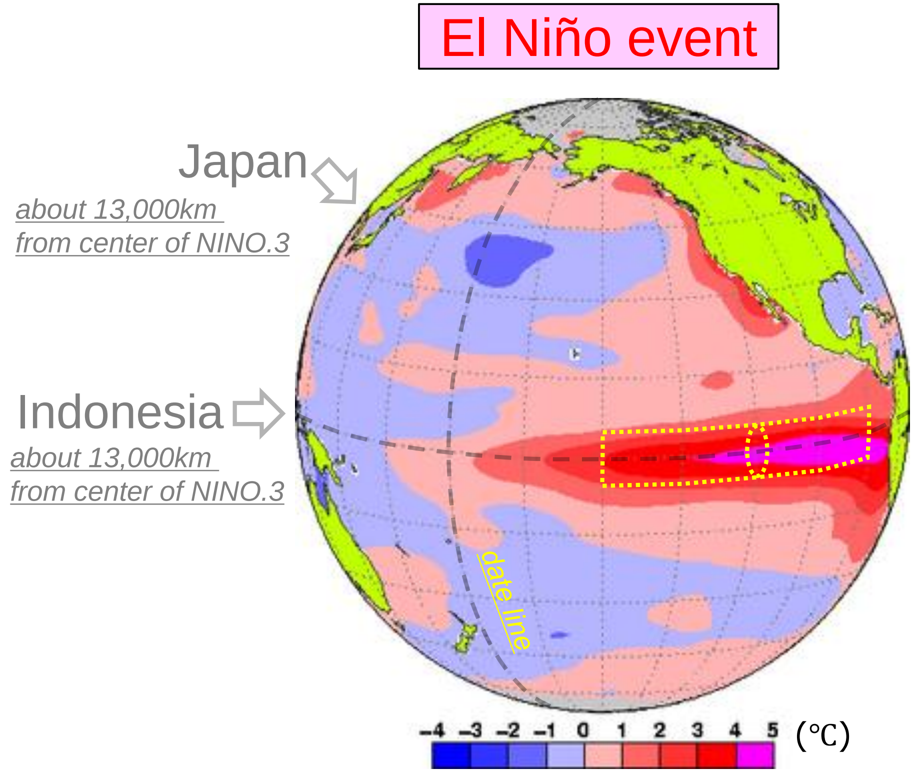
1981-2003



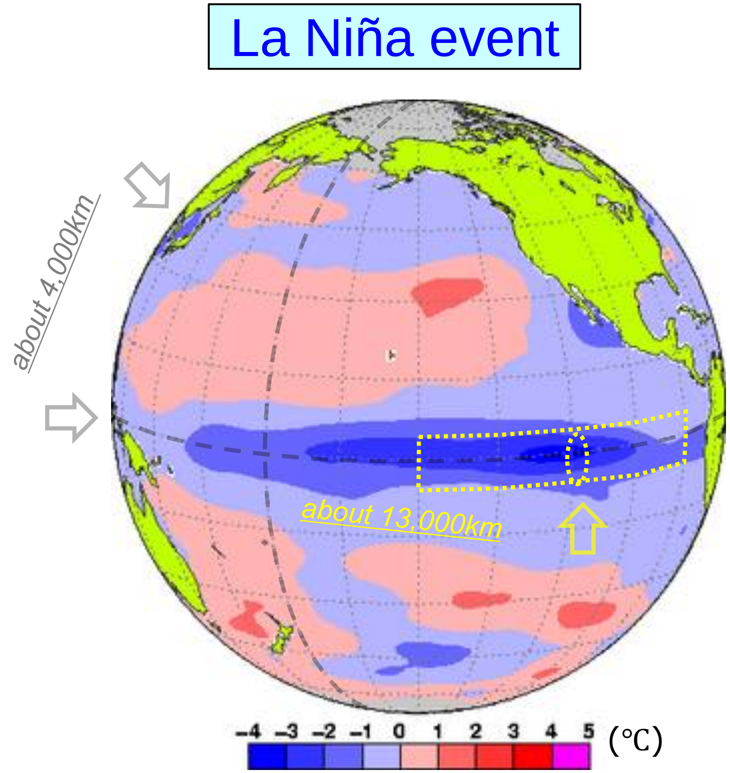
SST variabilities in the tropical Pacific Ocean

SST variabilities in the tropical Pacific Ocean

- El Niño and La Niña events are the largest SST variabilities.
- Both events occur every few years and continue about an year.
- JMA monitors El Niño/La Niña events with NINO.3 SST.



SST anomaly in November 1997



SST anomaly in December 1988

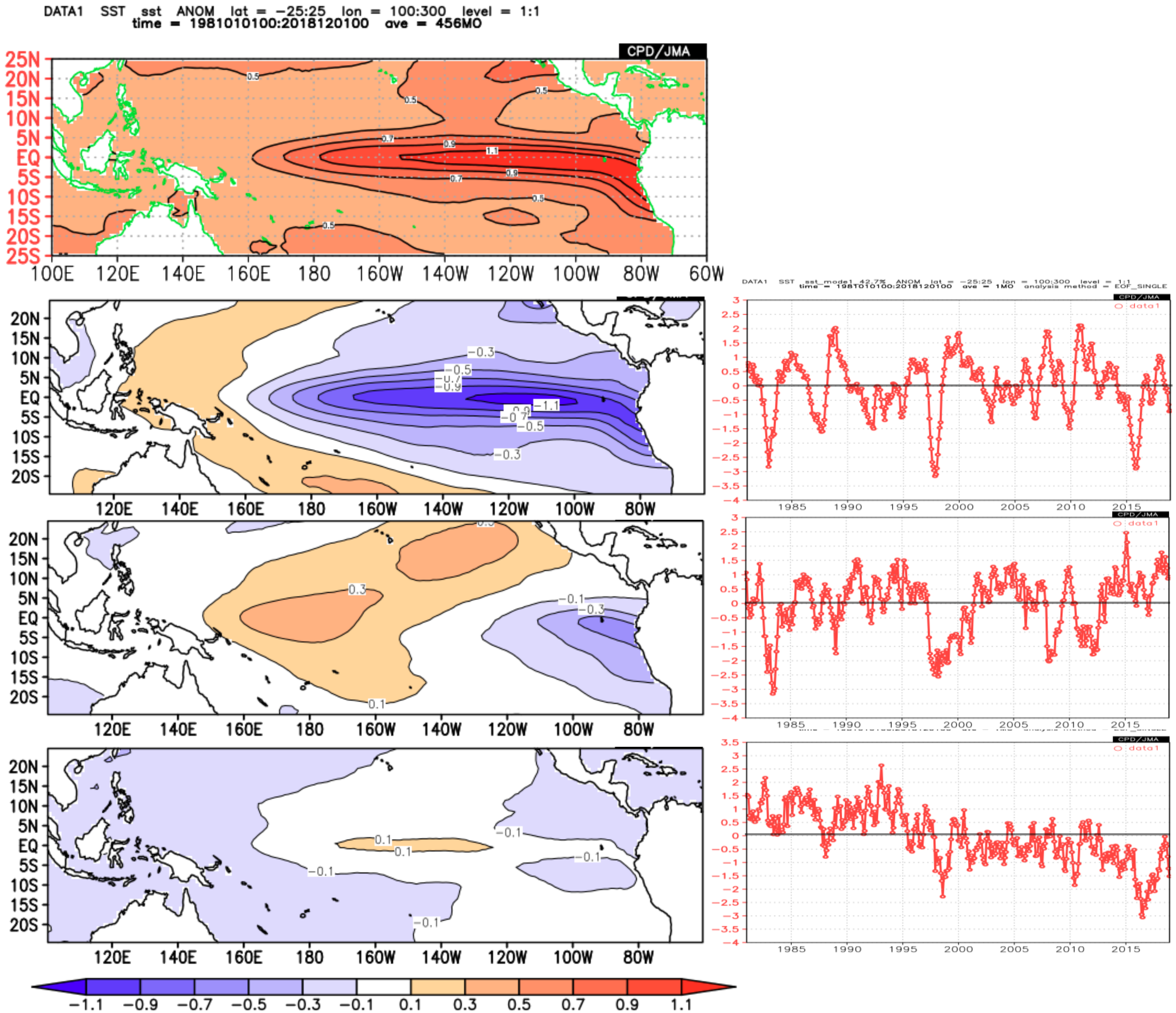
EOF of SSTA in the tropical Pacific ocean (1981.1 – 2018.12)

Standard deviation

EOF1 : 42.7% (ENSO)

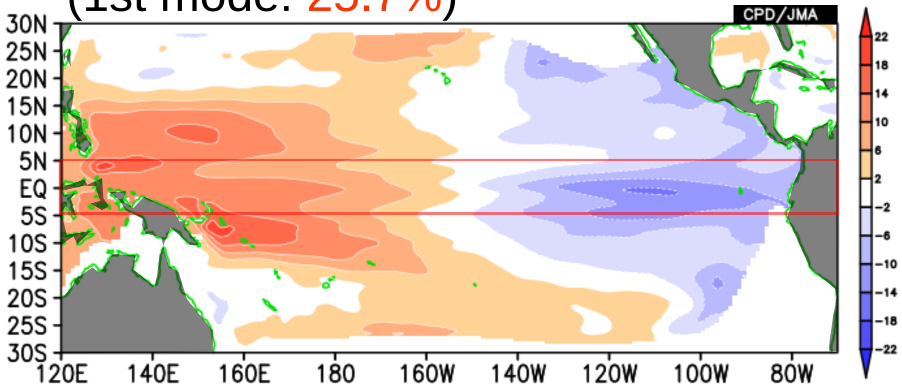
EOF2 : 10.4% (ENSO modoki)

Warming trend : 7.4%

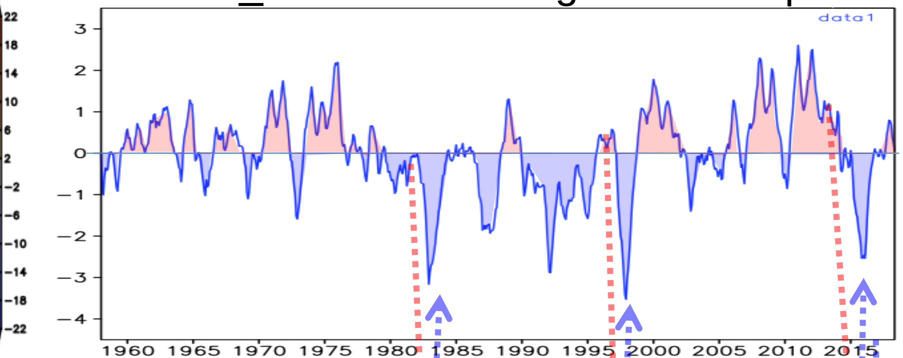


EOF of depth of 20° C (D20) in MOVE-G2 analysis

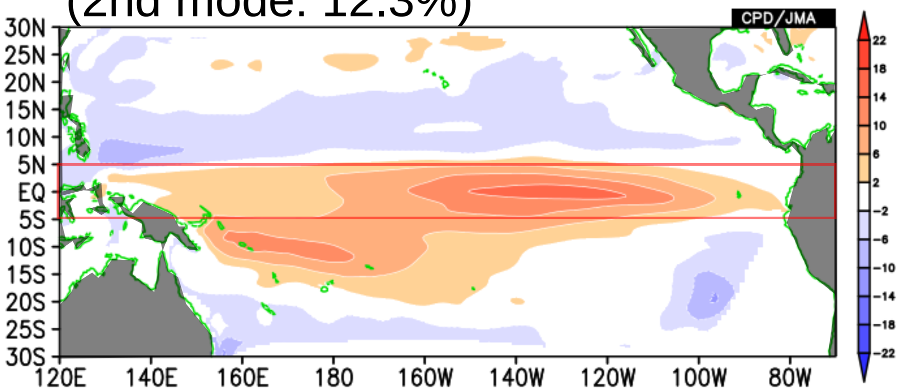
(1st mode: 25.7%)



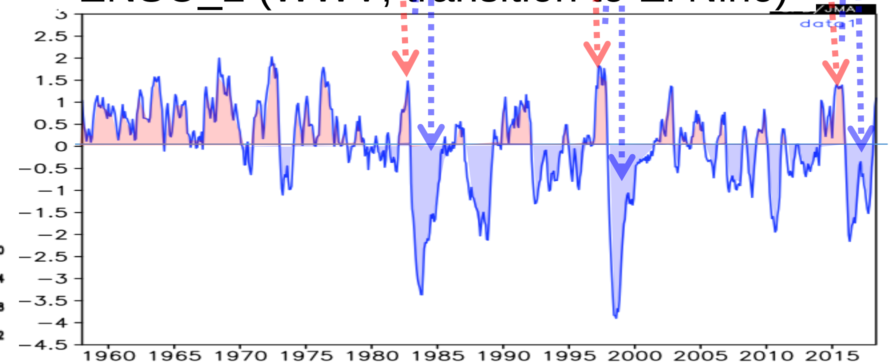
ENSO_1 La Niña or negative PDO phase ?



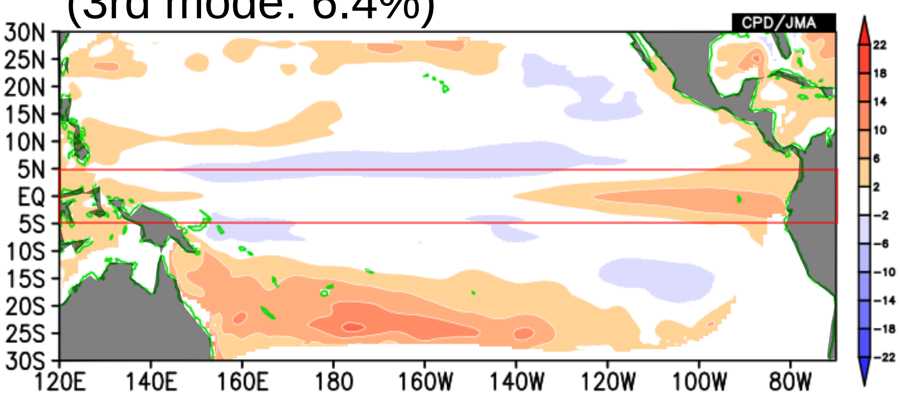
(2nd mode: 12.3%)



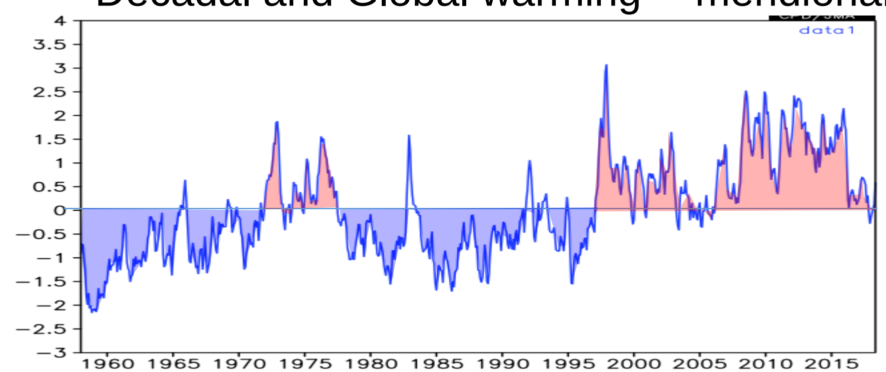
ENSO_2 (WWV; transition to El Niño)

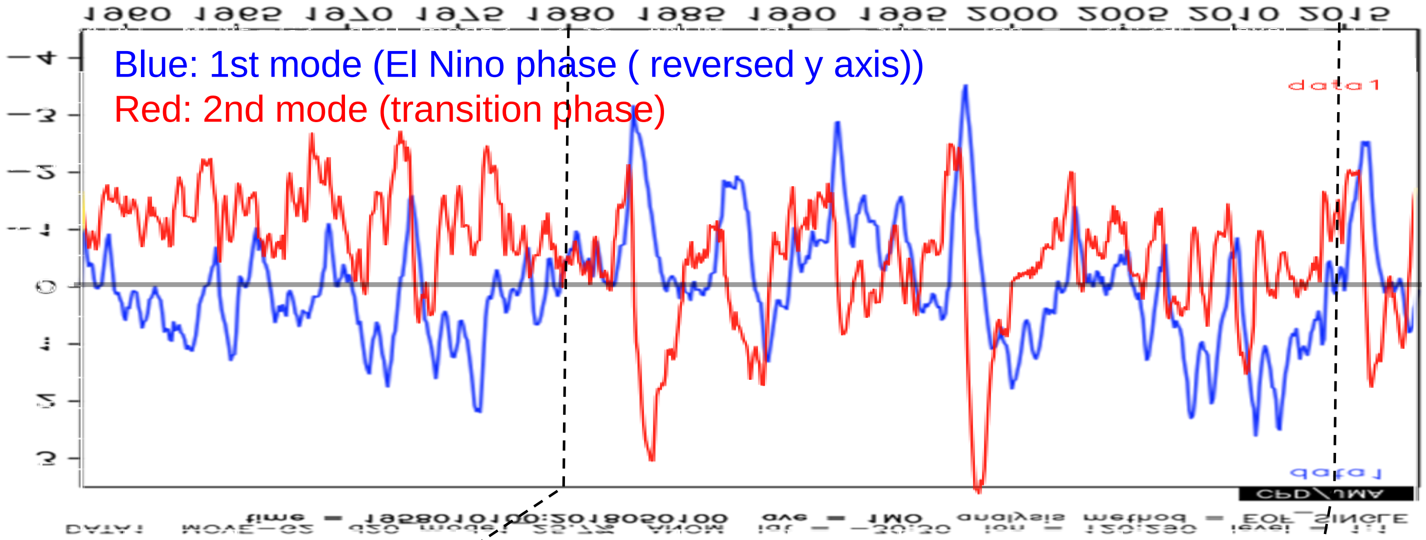


(3rd mode: 6.4%)



Decadal and Global warming -- meridional?

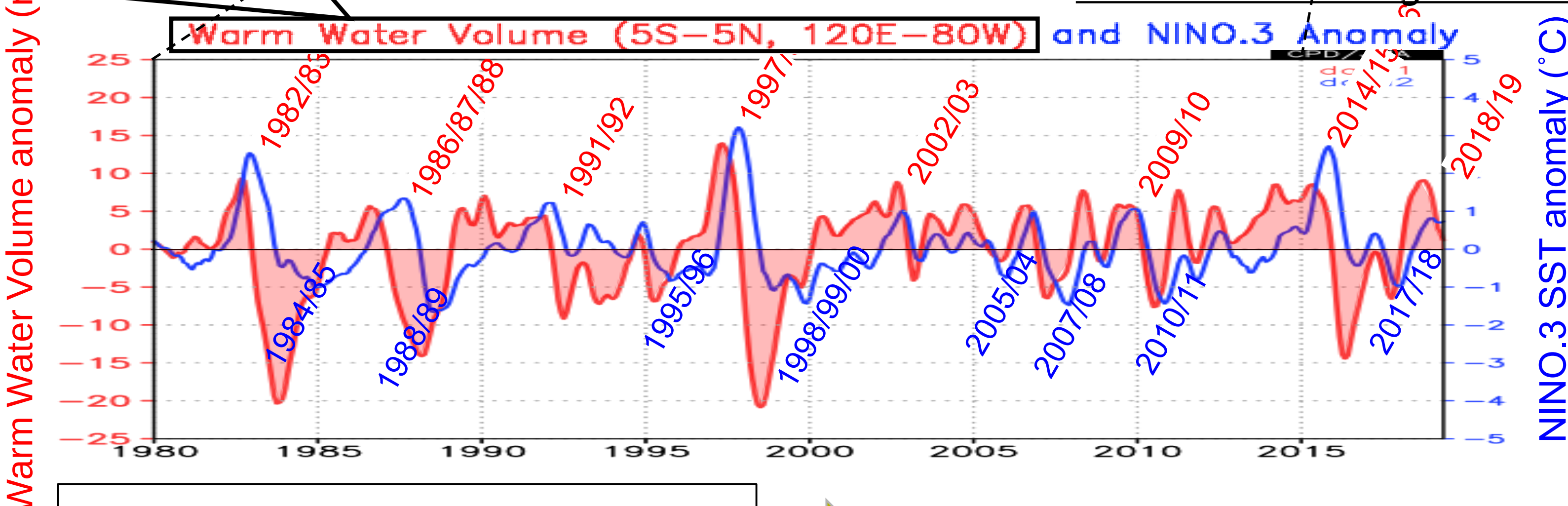




→ *ENSO mechanism:* Recharge-Discharge Action Oscillator

Zonally averaged depth of 20˚C isotherm in the equatorial Pacific

five-month running mean values



WWV leads to NINO.3 SST by one or two seasons

Predictable one or two seasons ahead

ENSO diversity

Characteristics of canonical (traditional) El Niño events

→ Typical features of El Niño events for a period from 1946 to 1976 (Rasmusson and Carpenter, 1982)

- 1982/83 El Niño event was exceptional. The development process were not preceded by anomalous warm, wet conditions in the eastern equatorial Pacific. (Philander 1990)

Locations of El Niño monitoring region

- NINO.3 (Rasmusson and Carpenter 1982 ?)
- NINO.3.4 (Trenberth 1997) location between NINO.3 and NINO.4
- Trans-Niño Index (TNI) (Trenberth and Stepaniak 2001) TNI = SSTA(NINO.1+2) /σ12 – SSTA(NINO.4)/ σ4

  TNI leads (lags) NINO.3.4 before (after) 1976/77 cf. Philander 1990

Phenomena contrasted with Canonical El Niño event

- Dateline El Niño ↔ Conventional El Niño (Larkin and Harrison, 2005)

  different US seasonal weather impacts from those conventionally identified (63,68,77,86,94)

  (additional El Nino seasons of NOAA's Nino3.4 definition in 2003 from conventional El Nino season)
- El Niño Modoki ↔ Canonical El Niño (Ashok et al. 2007)

  the second mode of EOF for the tropical Pacific SSTA

  (the first mode of EOF capture the Canonical ENSO pattern)
- WP (warm pool) El Niño ↔ CT (cold tongue) El Niño (Kug et al. 2009)

  compare the magnitudes of NINO.4 and NINO.3 SST anomalies
- CP (central Pacific) El Niño ↔ EP (east Pacific) El Niño (Kao and Yu, 2009)

  (EOF of SSTA exclude anomalies regressed with NINO.1+2) ↔ (EOF of SSTA exclude anomalies regressed with NINO.4)

Magnitudes of El Niño events ?

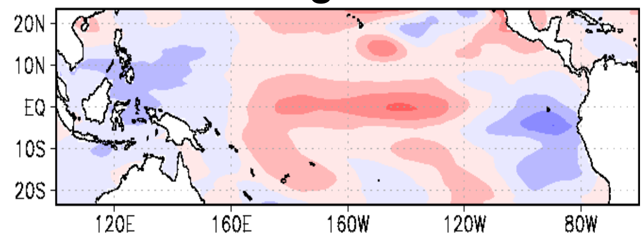
- Four strong El Nino events: 1972/73, 1982/83, 1997/98, 2014/15/16
- Weak (0.5≦ONI＜1.0)／Moderate (1.0≦ONI＜1.5)／Strong (1.5≦ONI)

(ONI :three-month moving average of NINO.3.4 SSTA of ERSSTv4 (NOAA))

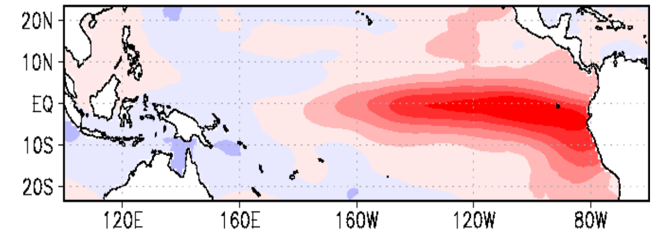
ENSO diversity - Two types of ENSO

Observed
SST anomalies

Aug2004

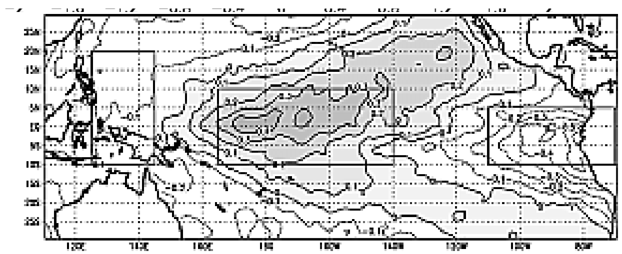


Nov1997

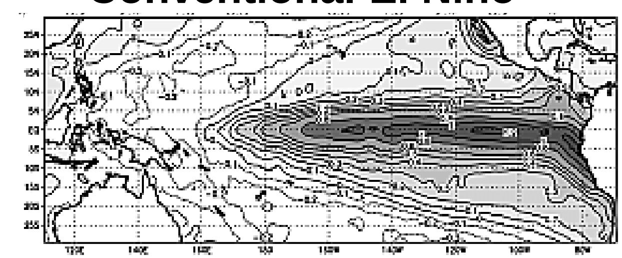


Ashok et al. (2007)
EOF

El Niño Modoki

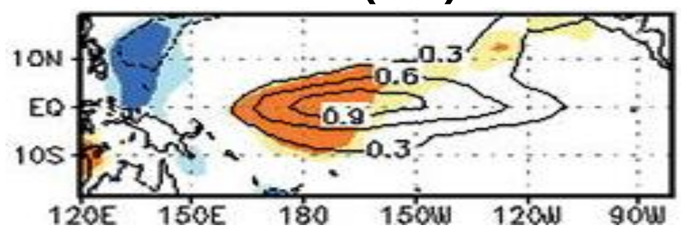


Conventional El Niño

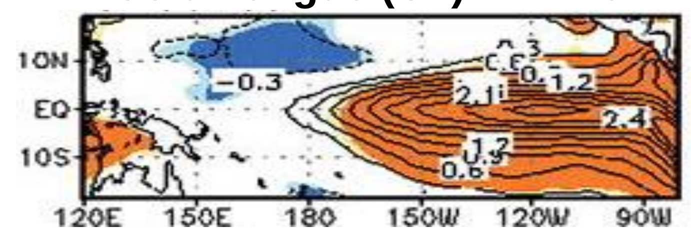


Kug et al. (2009)
Nino.3 vs. **Nino.4**

Warm Pool (WP) El Niño

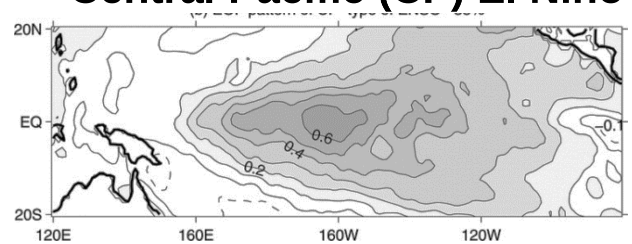


Cold Tongue (CT) El Niño

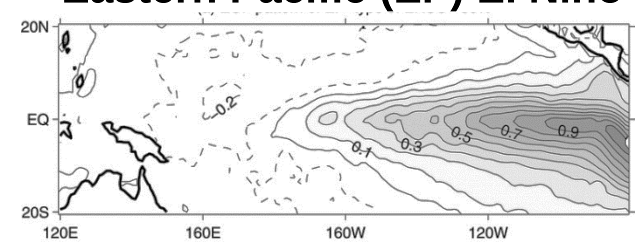


Kao and Yu (2009)
EOF - regression

Central Pacific (CP) El Niño

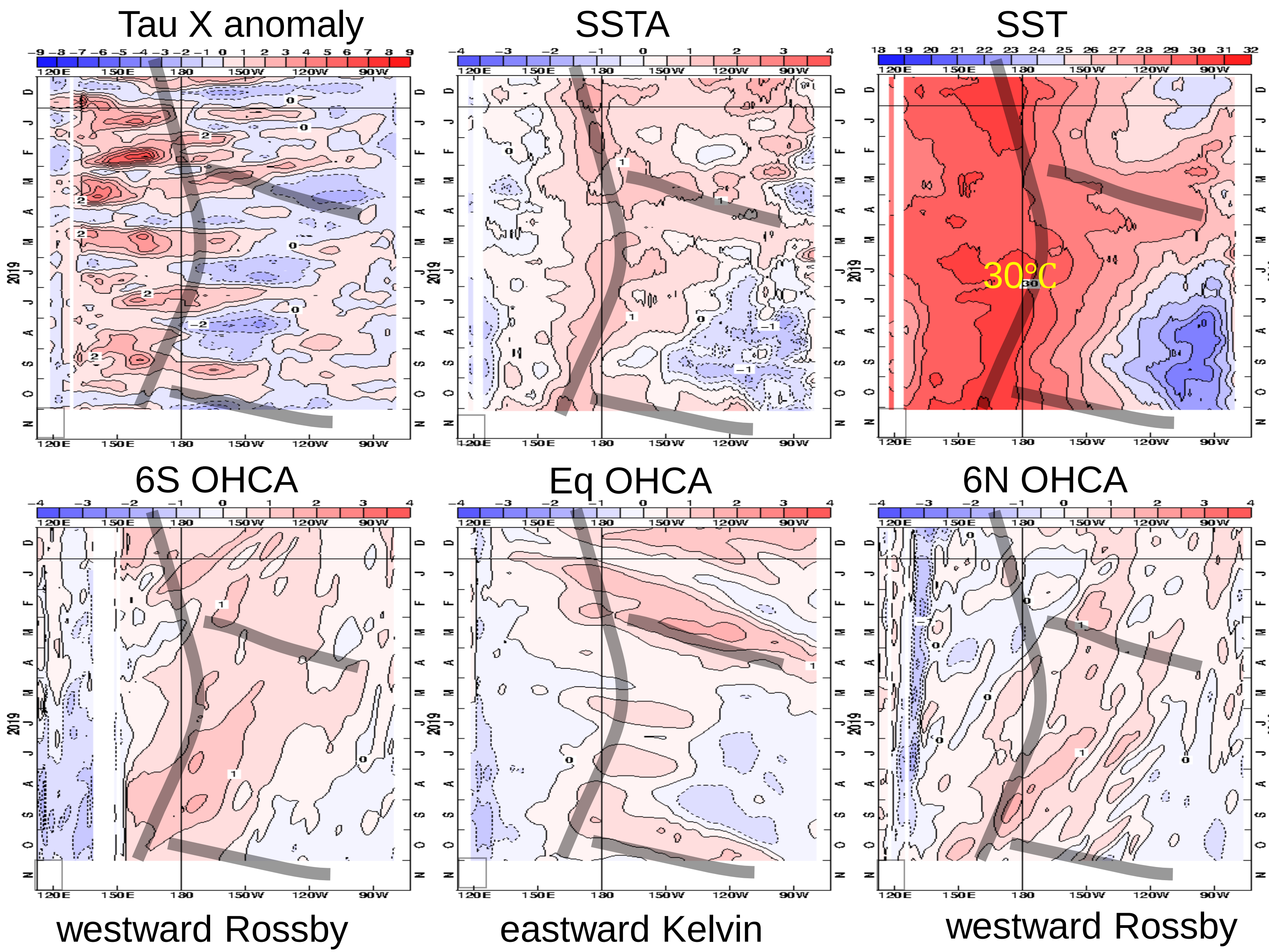


Eastern Pacific (EP) El Niño



Recent air – sea interactions in the equatorial central Pacific

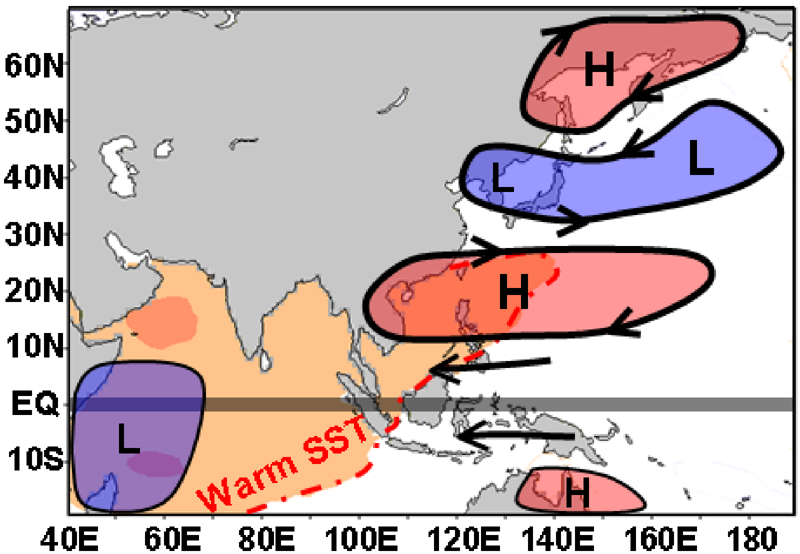
(2018.12 – 2019.10 El Nino modoki season)



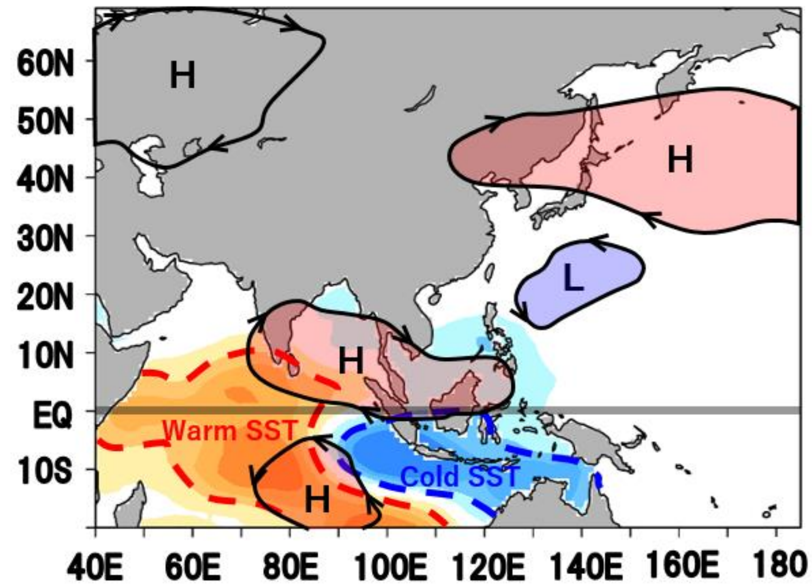
SST variabilities in the tropical Indian Ocean

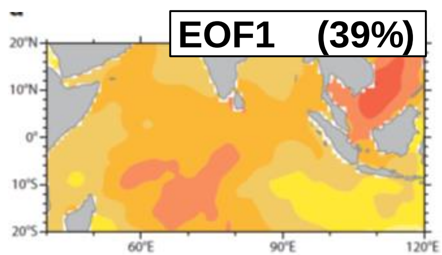
SST variabilities in the tropical Indian Ocean

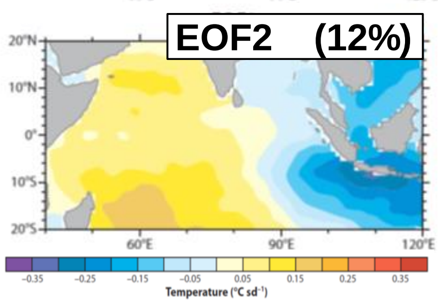
Basin wide mode (JJA composite)
(capacitor effect related to ENSO)

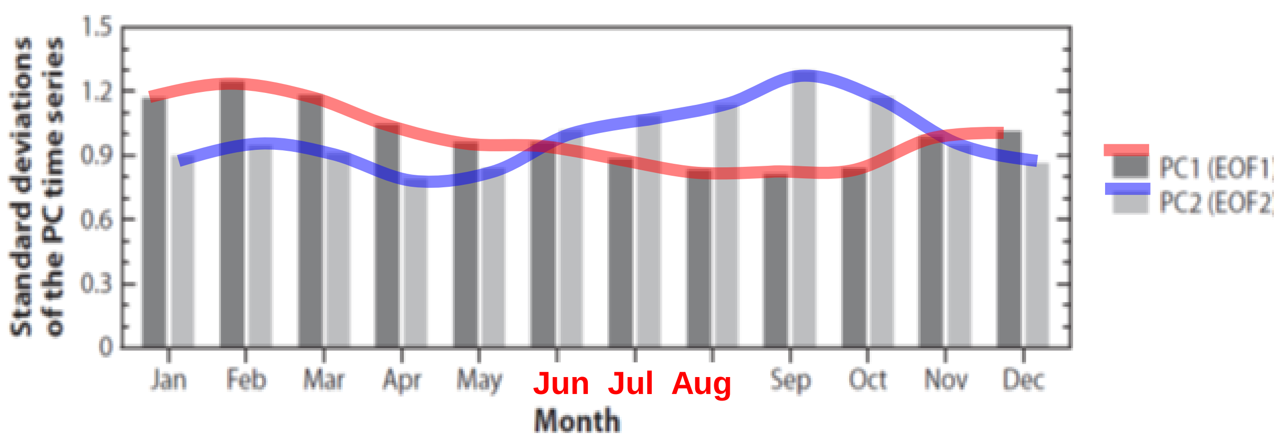


Indian ocean dipole mode
(ASO composite; intrinsic mode)



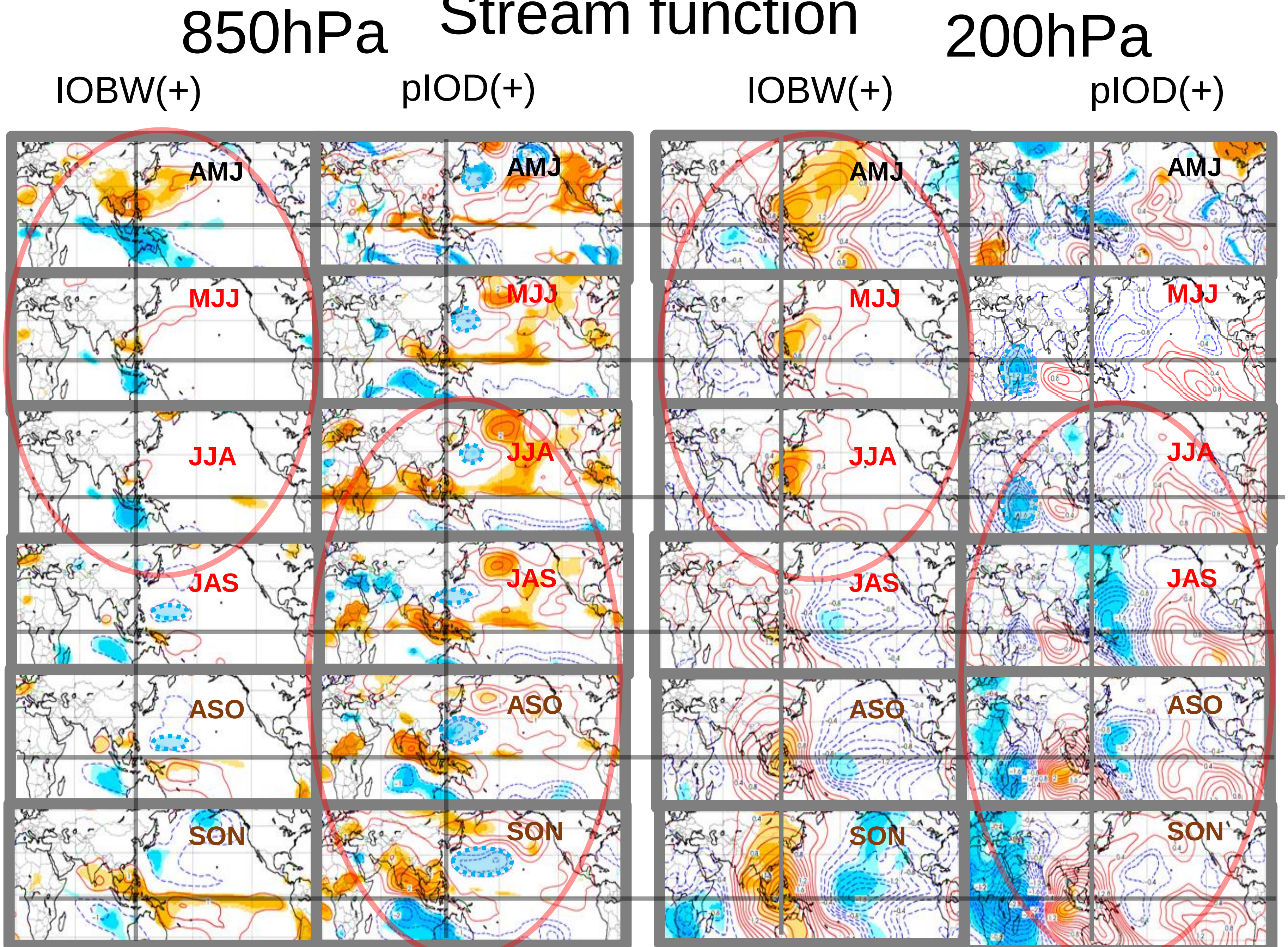






Deser et al. (2010) :HadISST data set during 1900–2008

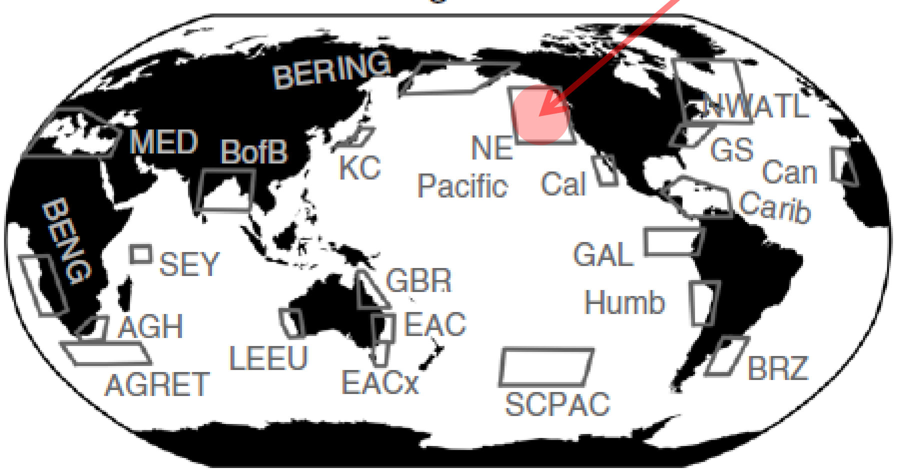
Stream function

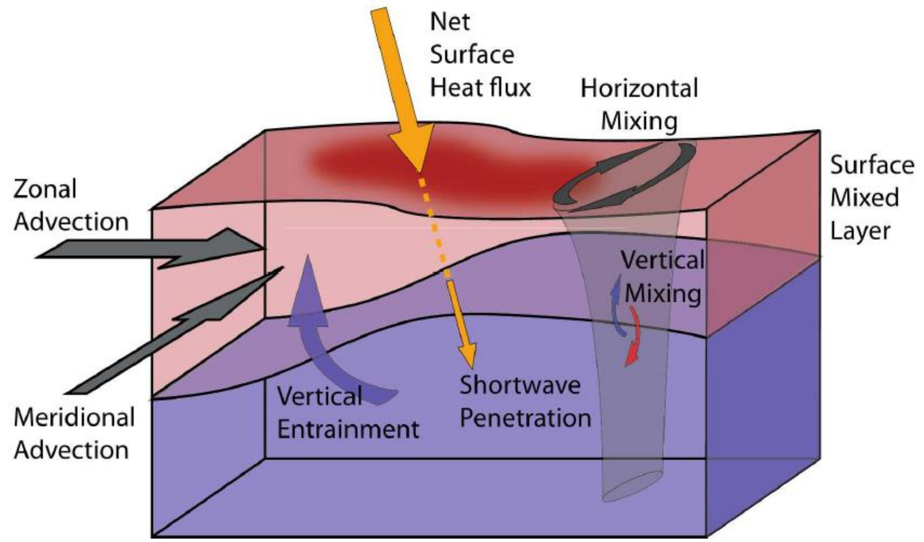


SST variabilities in the mid latitude Pacific Ocean

Marine Heatwaves (MHWs)

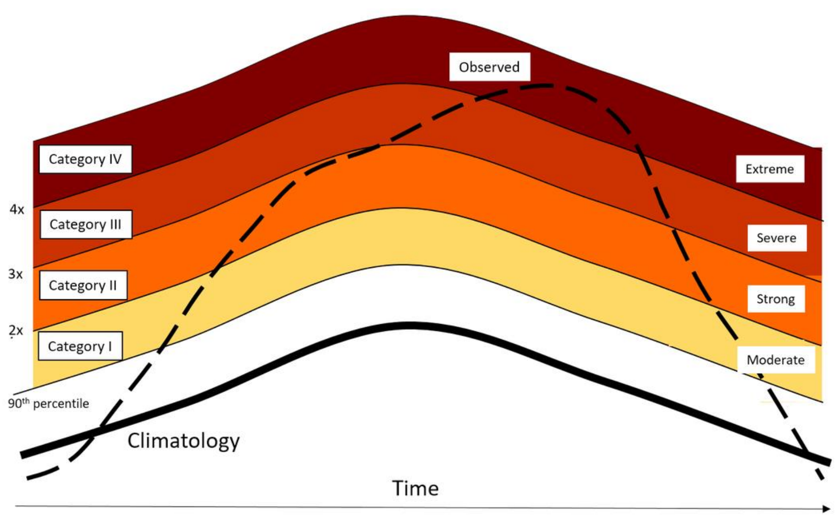
Holbrook et al. 2019





Local processes which can alter surface mixed layer temperature (Holbrook et al. 2019)

Definition (Hobday et al. 2018)



8 Sep 2019 Guardian news

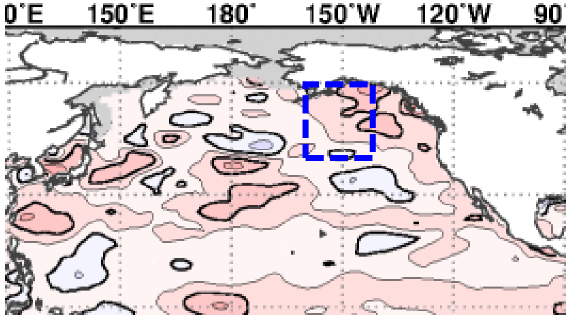
Marine heatwave hits Pacific, raising fears of a new hot **'blob'**

This article is more than 1 month old

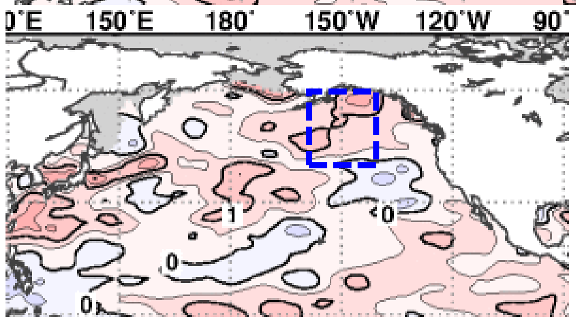
Phenomenon could be as damaging as 'the blob' that caused algae blooms and killed sea lions several years ago

“Blob” SST anomaly pattern which is frequently seen recently

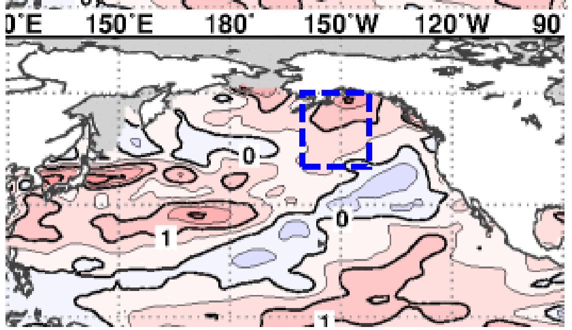
2019.1



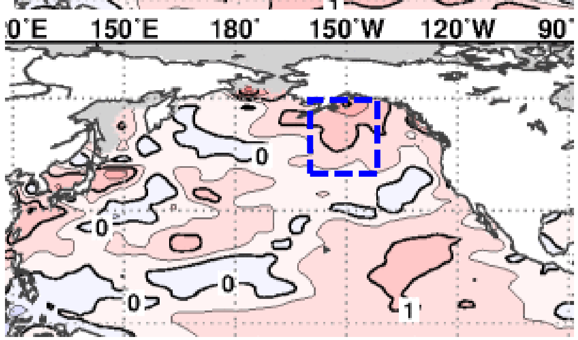
2019.2



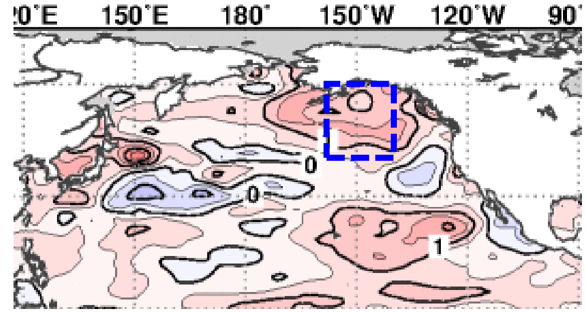
2019.3



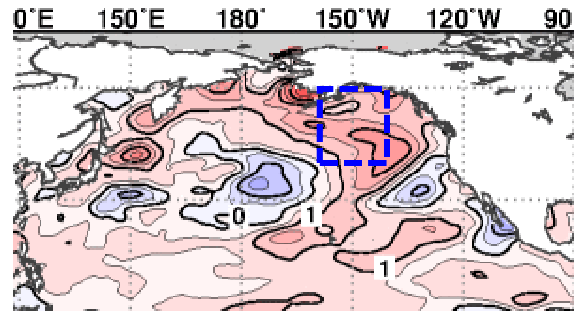
2019.4



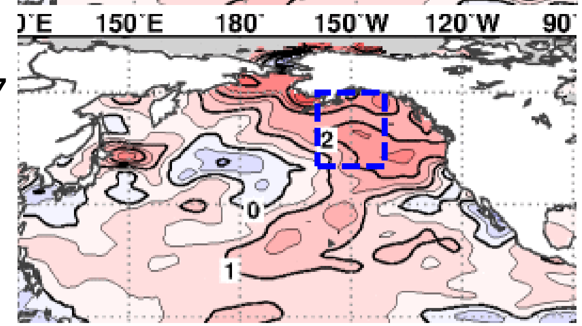
2019.5



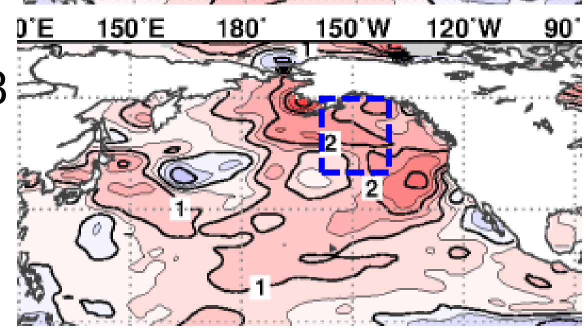
2019.6



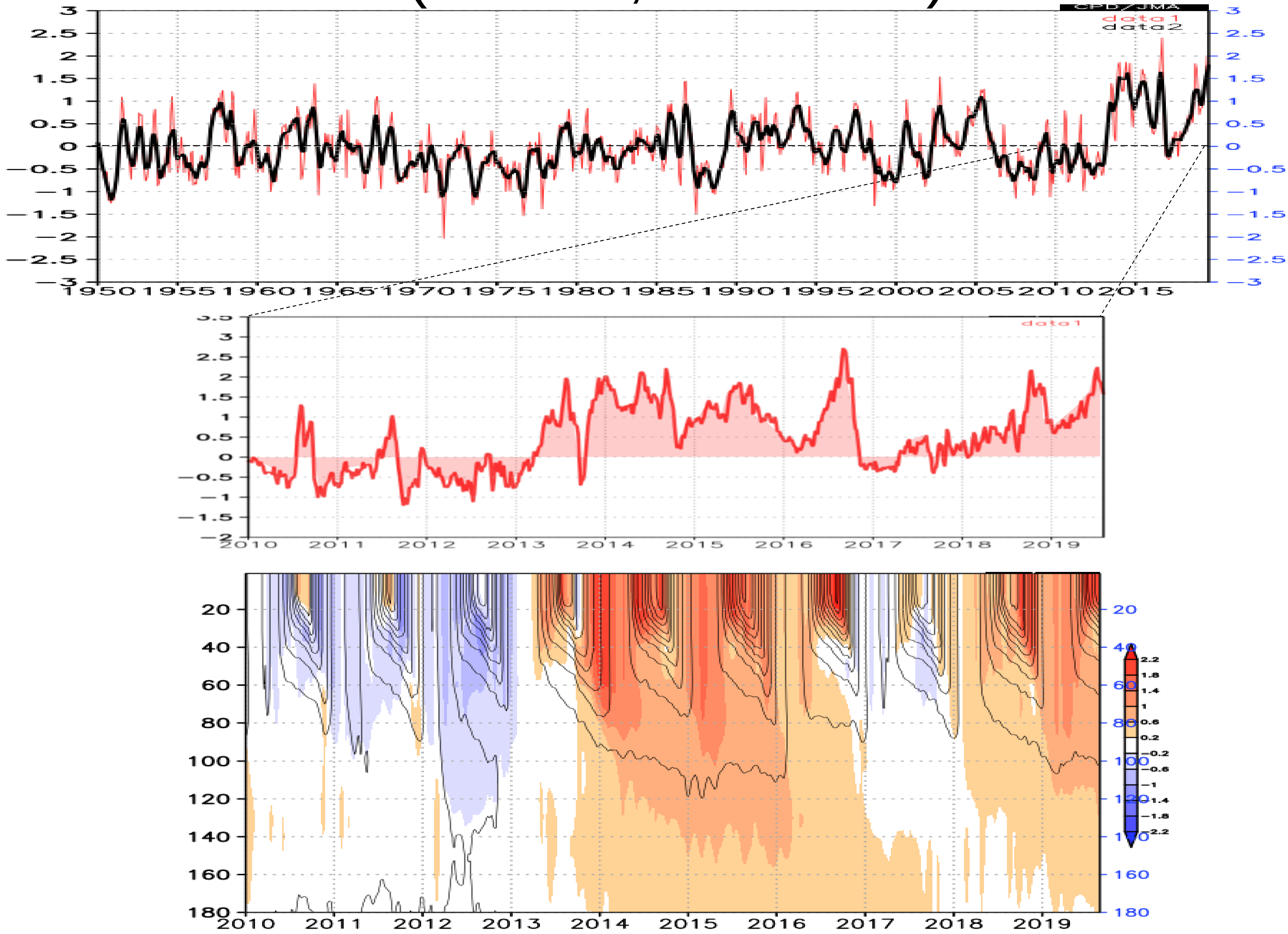
2019.7



2019.8



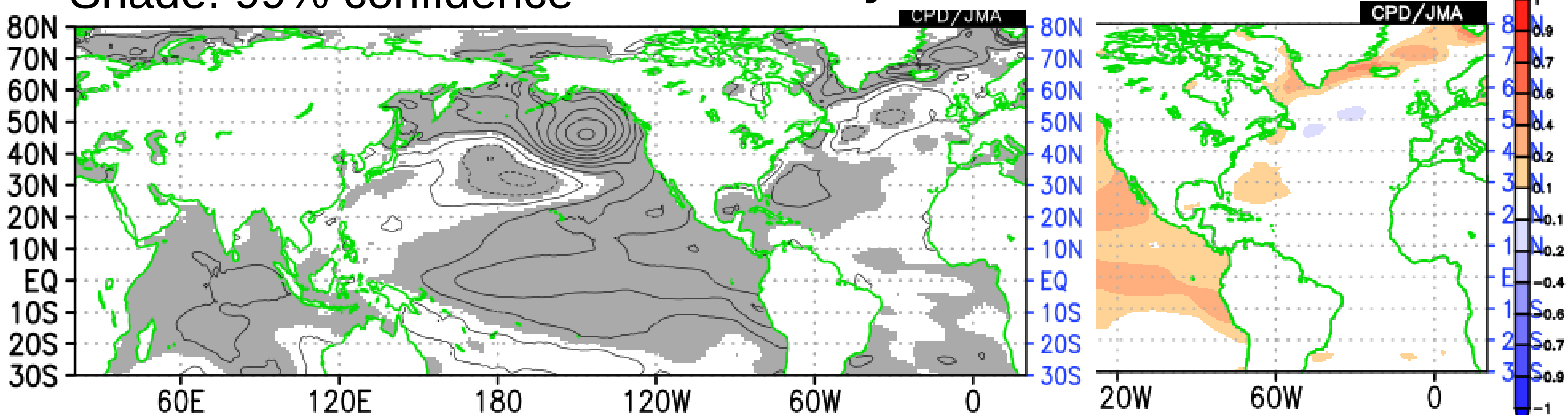
Blob SSTA (40-60N, 200-220E)



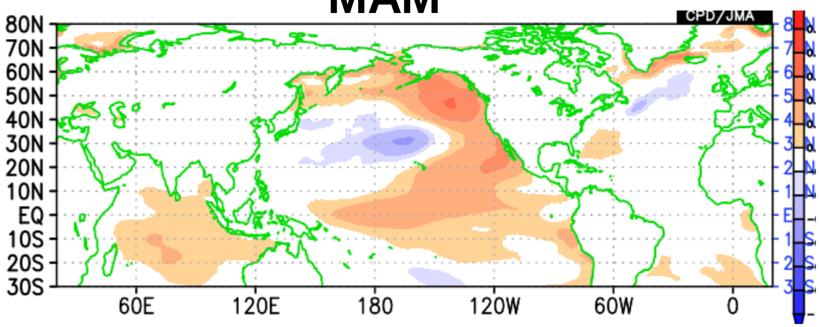
SSTA regressed with Blob SSTA (40-60N, 200-220E)
(1950.1 - 2019.8)

Shade: 99% confidence

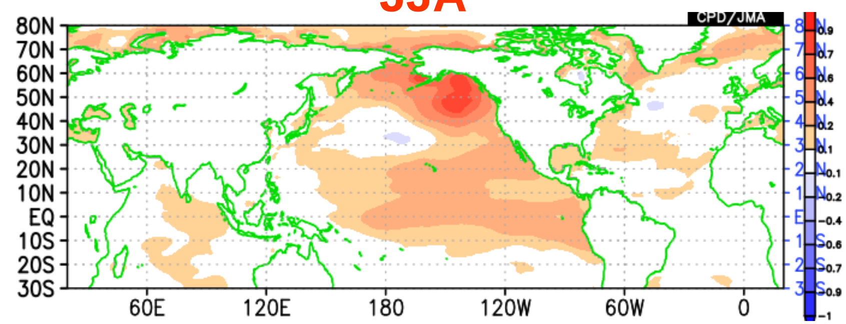
monthly



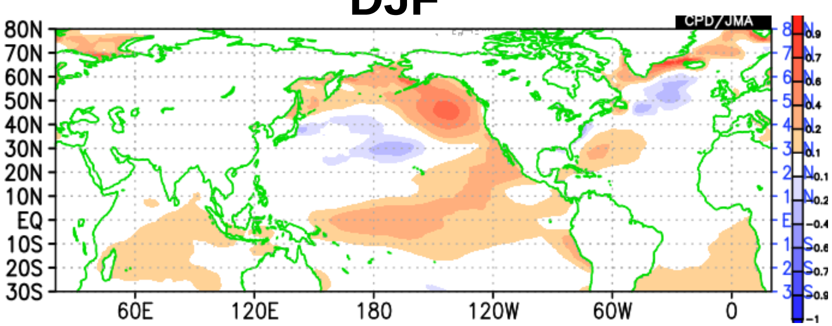
MAM



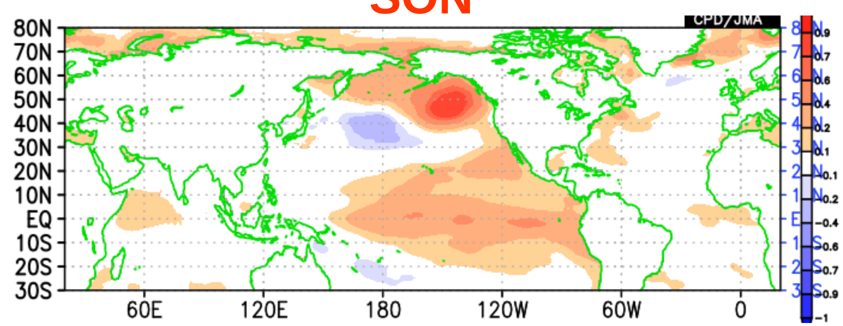
JJA



DJF



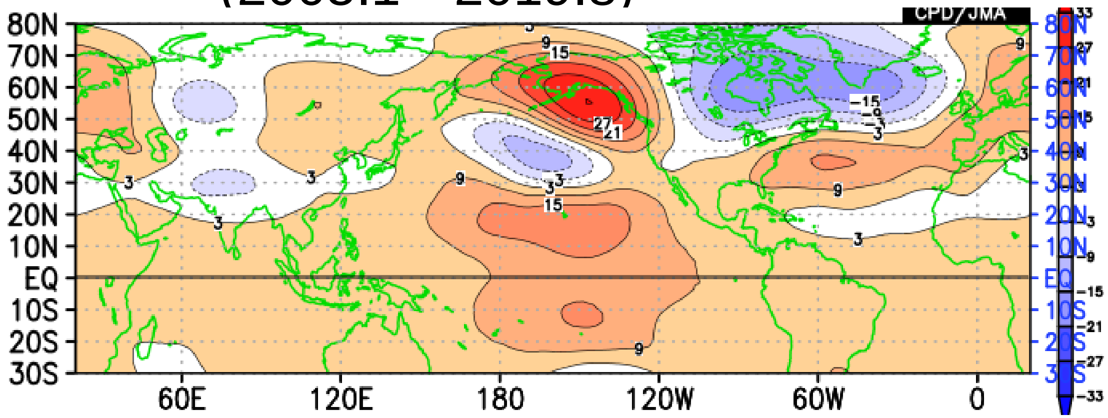
SON



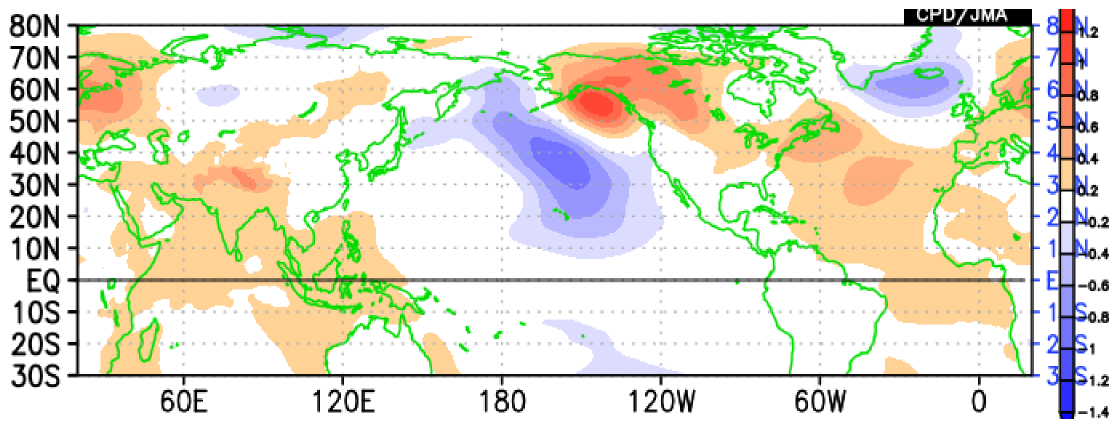
Regression with Blob SSTA (40-60N, 200-220E)

(2005.1～2019.8)

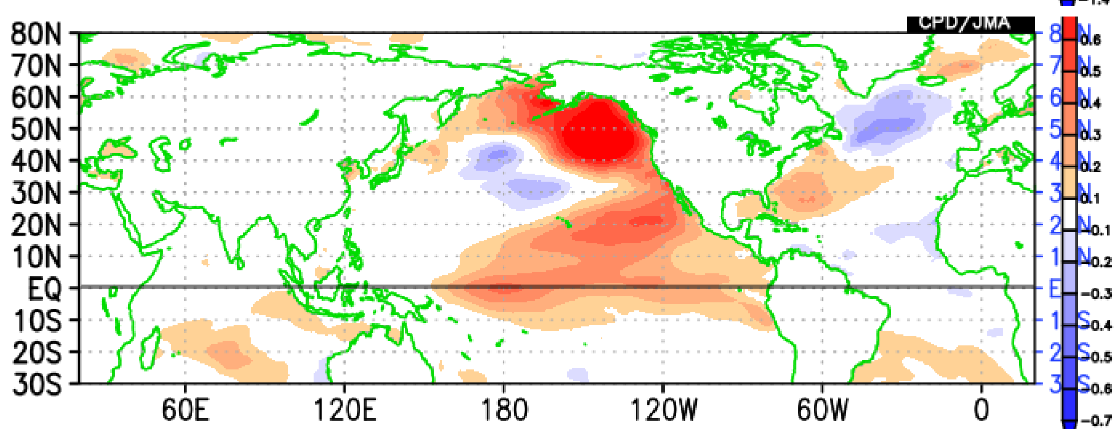
200hPa height



Sea level pressure



SST



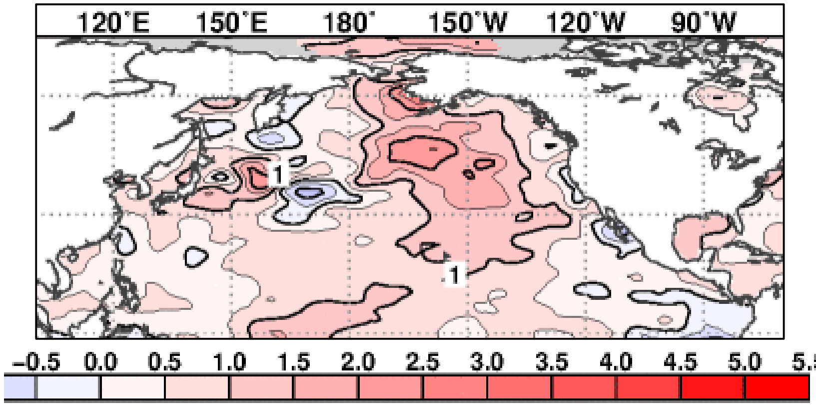
PDO / NPGO

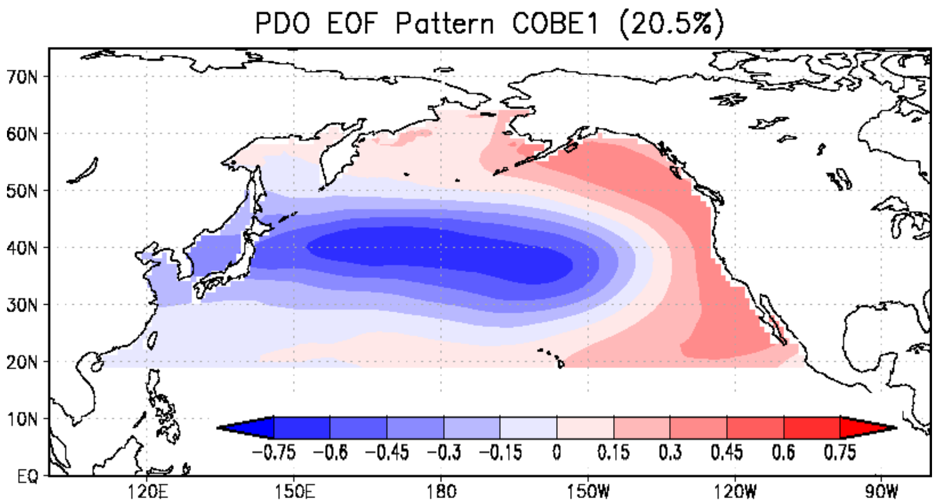
Pacific Decadal Oscillation / North Pacific gyre Oscillation

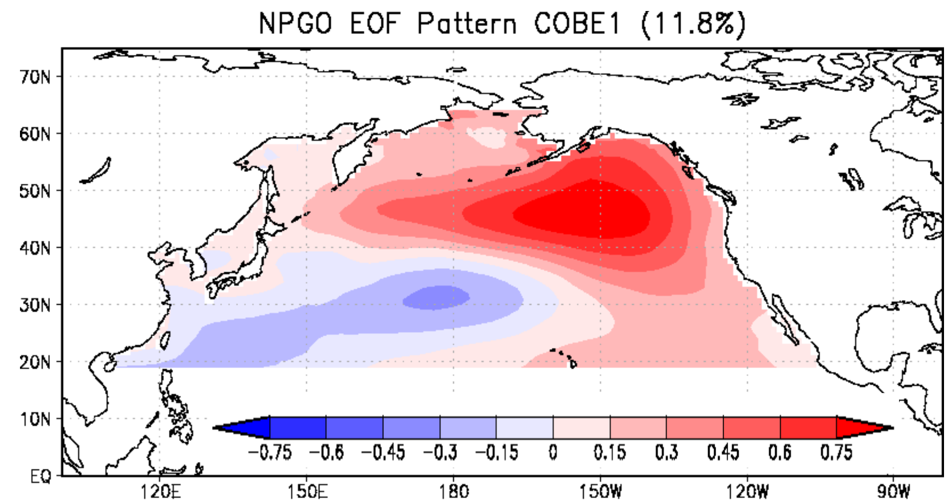
Mantua et al. (1997) / Di Lorenzo et al. (2008)

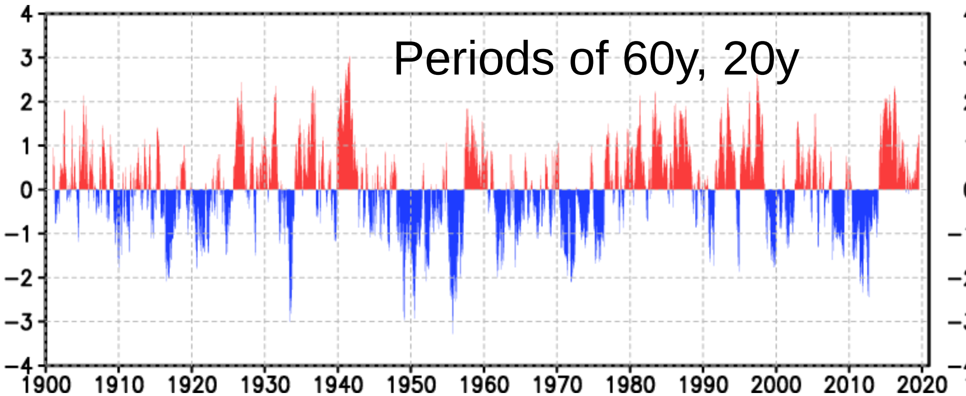
EOF of SSTA in the North Pacific northward of 20N (1901-2000)

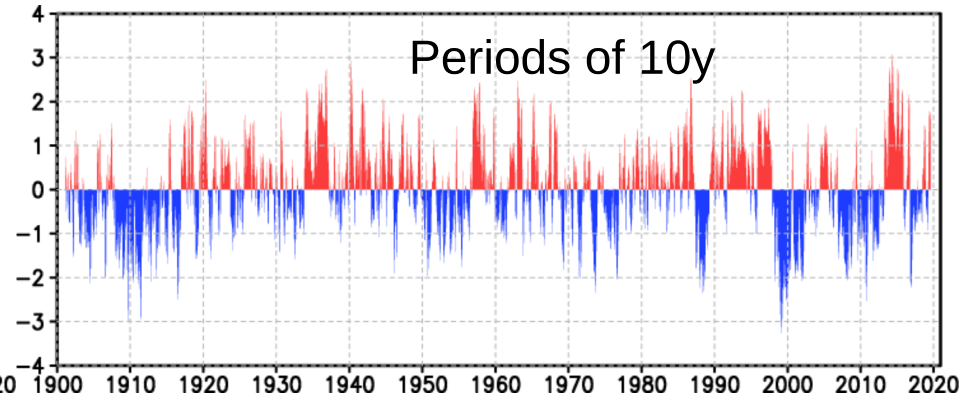
2019.10











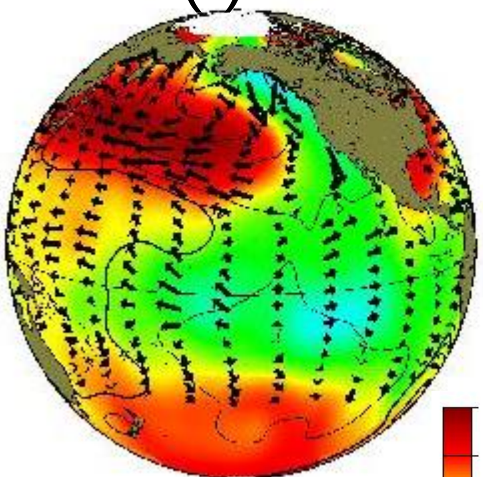
PDO / NPI

Pacific Decadal Oscillation / North Pacific Index

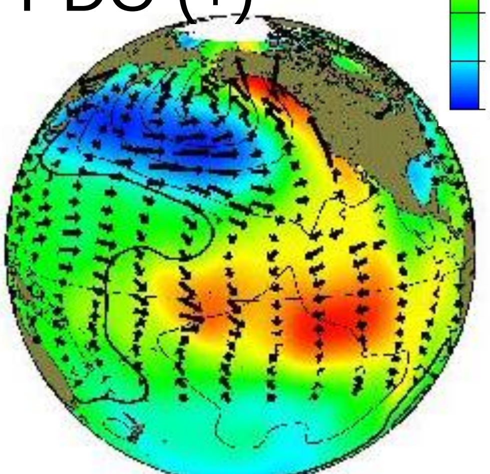
Mantua et al. (1997) / Trenberth and Hurrell (1994)

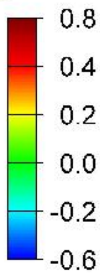
SST and WIND anomalies

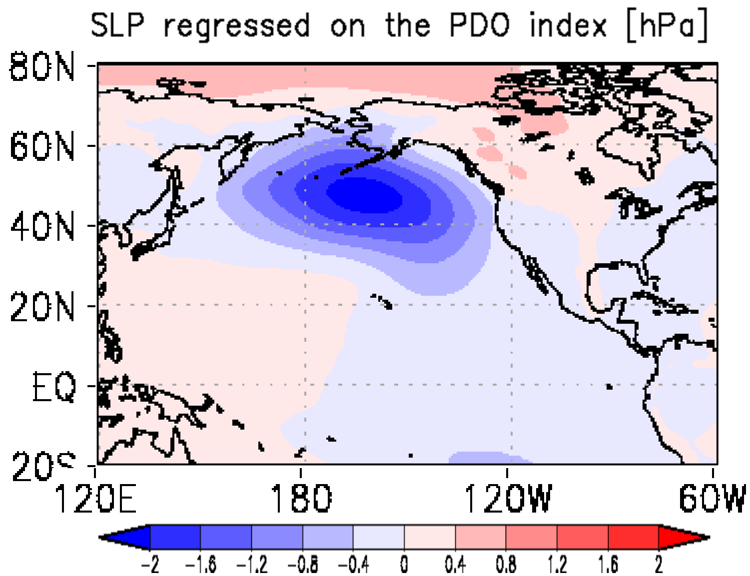
PDO (-)



PDO (+)

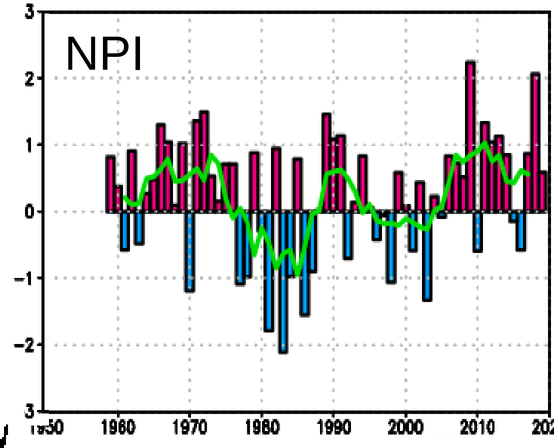


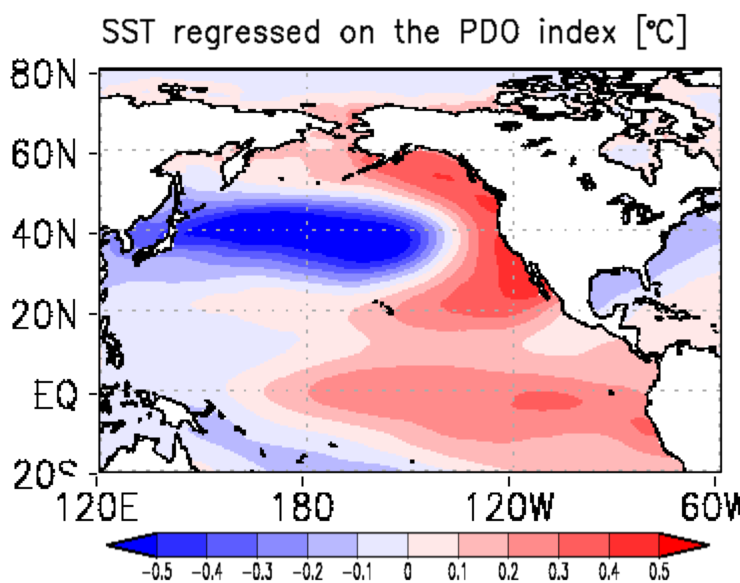


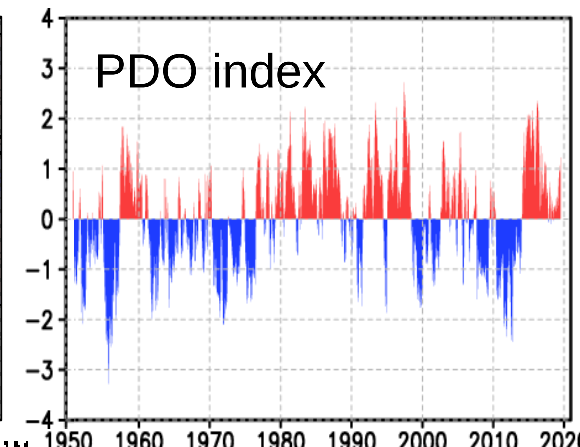


Intensity of Aleutian Low

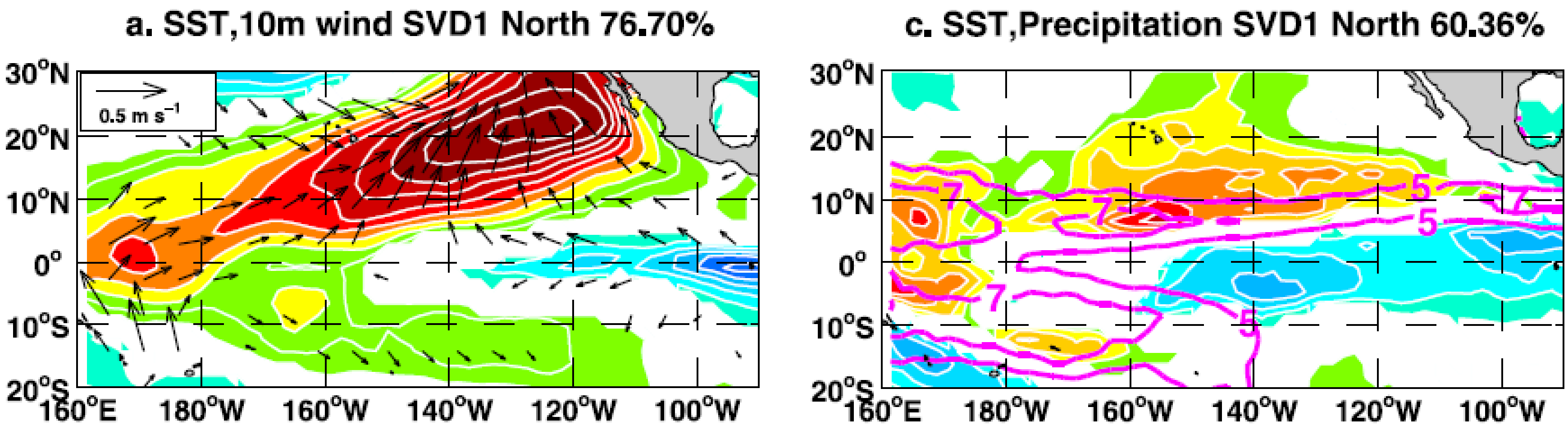
(Standardized SLP of 30ºN-65ºN, 160ºE-140ºW)



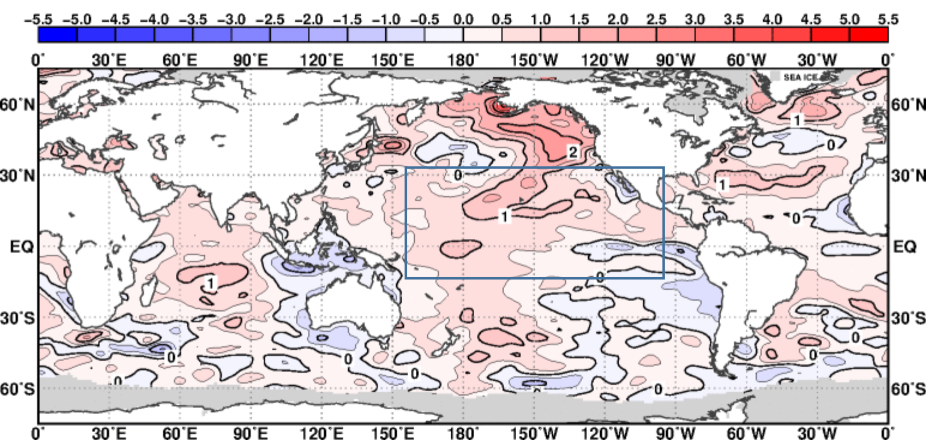


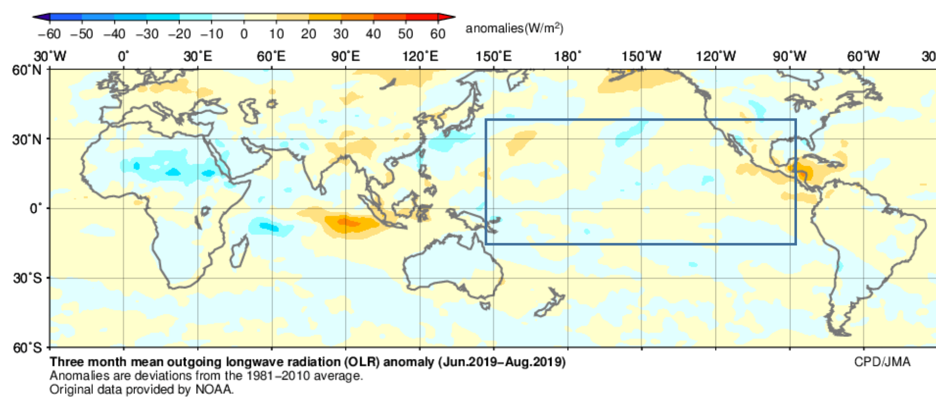


SST variabilities of the meridional mode in the Pacific



Min et al. (2017)



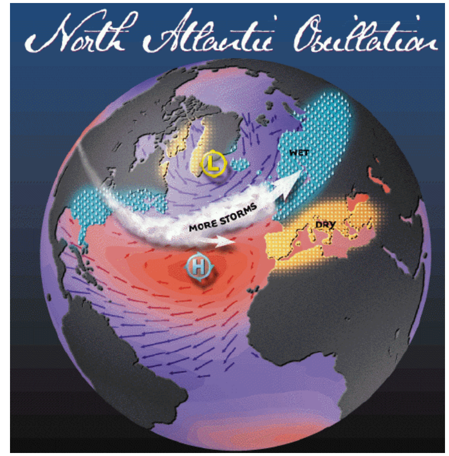


Jun – Aug 2019

SST variabilities in the Atlantic Ocean

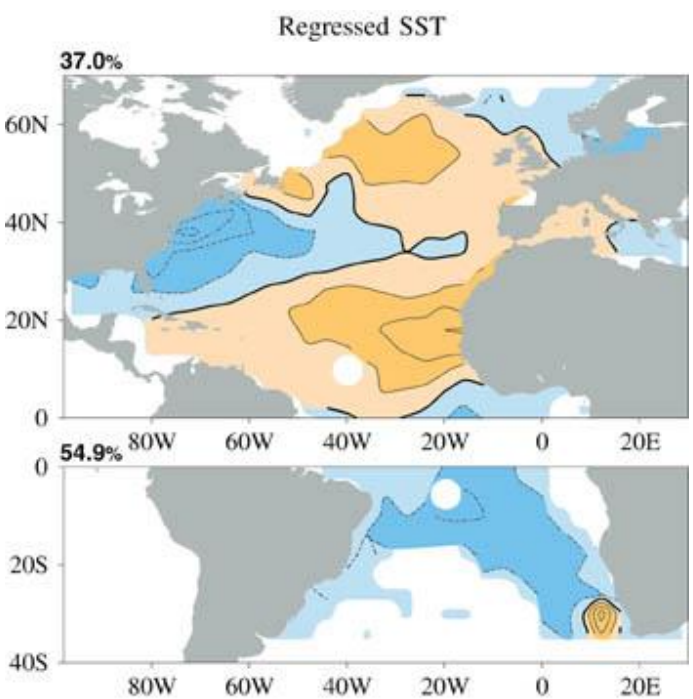
North Atlantic Oscillation (NAO)

AO plus   AO minus



NAO plus
strong Island low
strong Azores high

NAO minus
weak Island low
weak Azores high

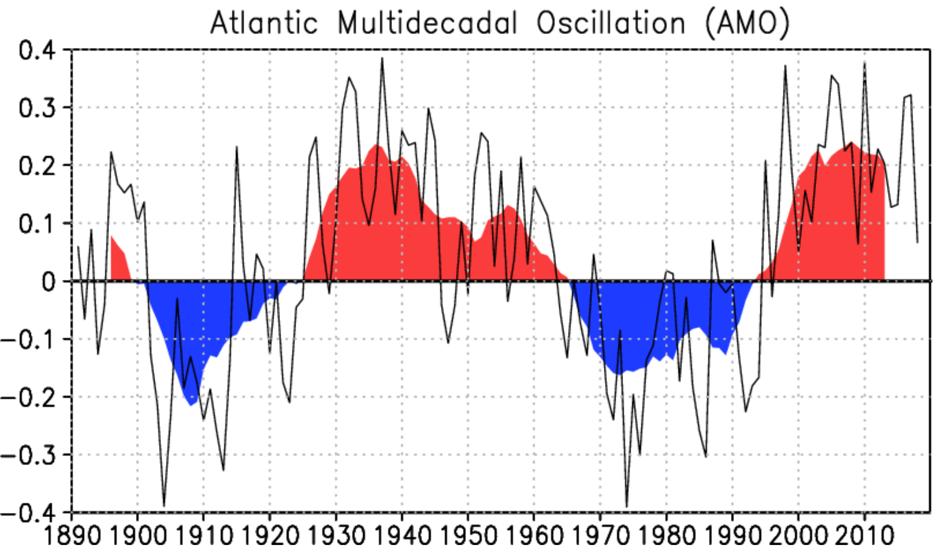


SST tripole pattern in th North Pacific and Atlantic dipole pattern

Tanimoto and Xie (2002)

Patterns indicated left are seen during the minus phase of NAO/AO pattern

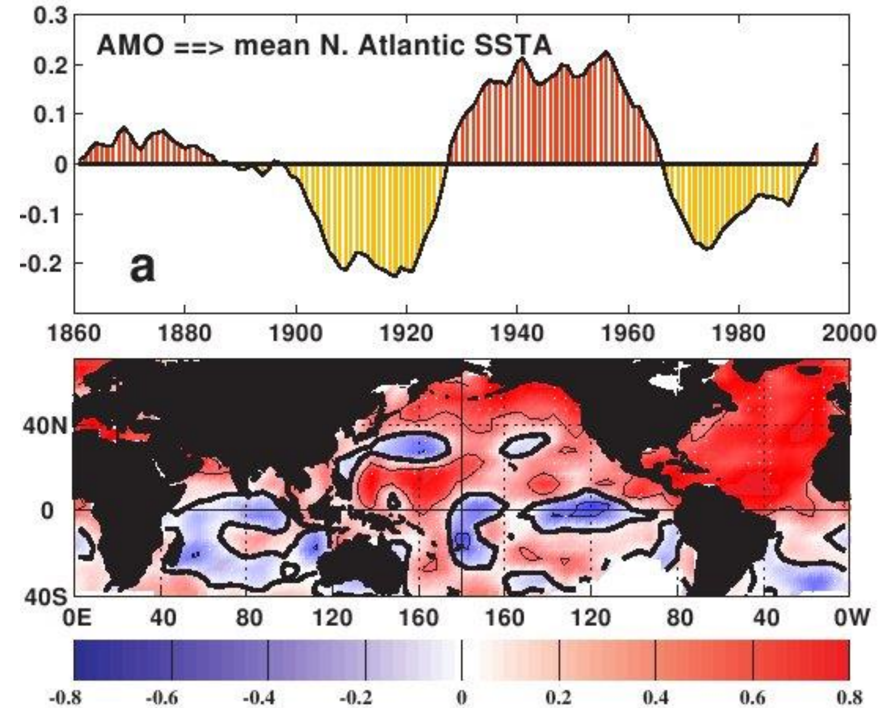
Atlantic Multi-decadal Oscillation(AMO)



Variability of North Pacific SSTA with 60-100 year periods.
It is a natural variability continued from more than 1000 years ago. It affects Hurricane, and climate in USA, Europe.

AMO estimated by COBE-SST
Trends from 1901 to 2000 are removed from **North Atlantic annual mean SSTA (EQ-60N)**
Black line indicate annual mean SST anomalies
Shade : 11 year moving average

http://www.data.jma.go.jp/gmd/kaiyou/data/db/climate/knowledge/atl/atlantic_decadal.html

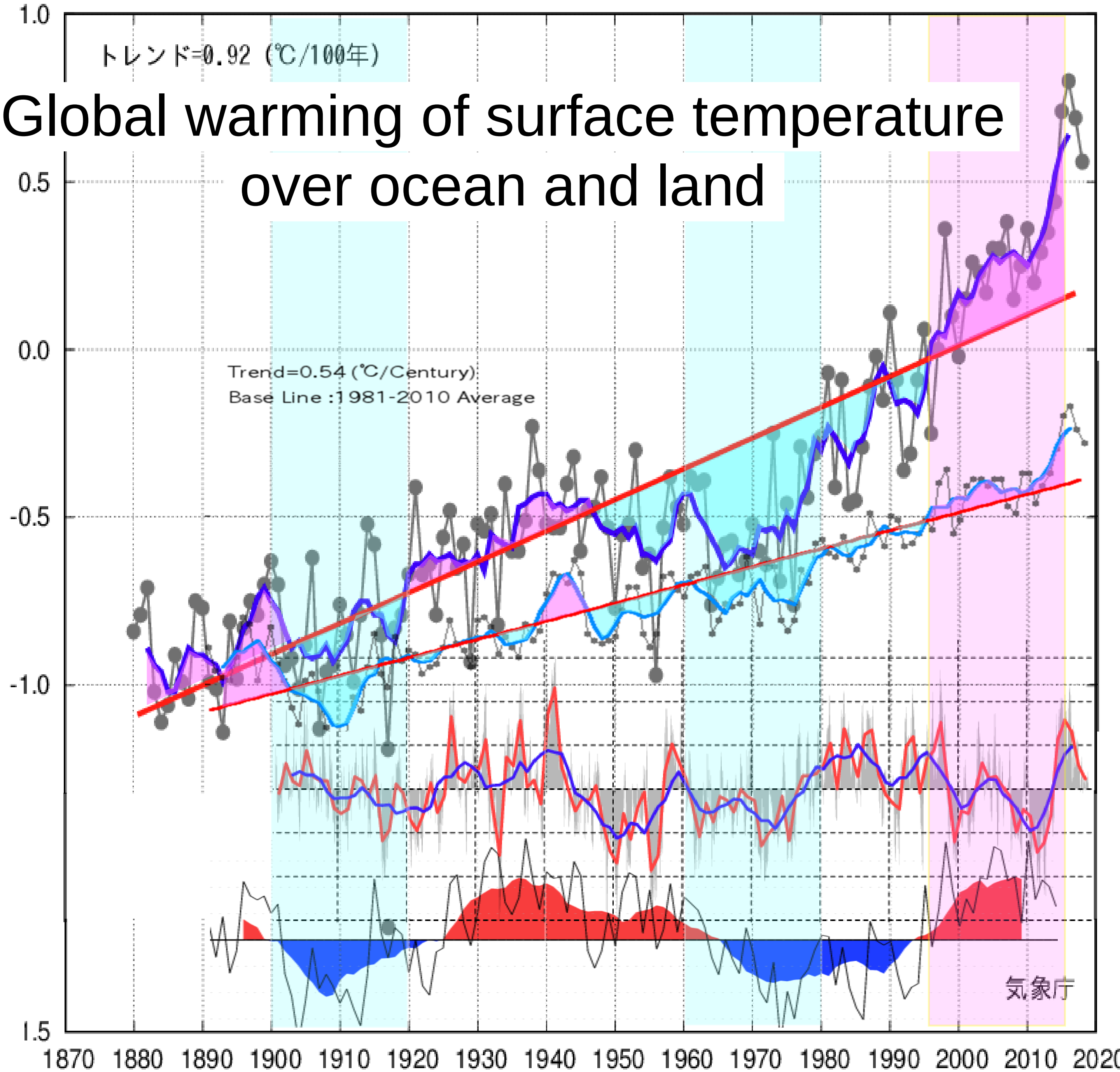


Upper panel: AMO index: the ten-year running mean of detrended Atlantic sea surface temperature anomaly (SSTA, ° C) north of the equator. Lower panel: Correlation of the AMO index with gridded SSTA over the world ocean (all seasons). The thick contour is zero and thin contours denote the 95% significance level.

http://www.aoml.noaa.gov/phod/amo_fig.php

Global warming in the ocean

Global warming of surface temperature over ocean and land



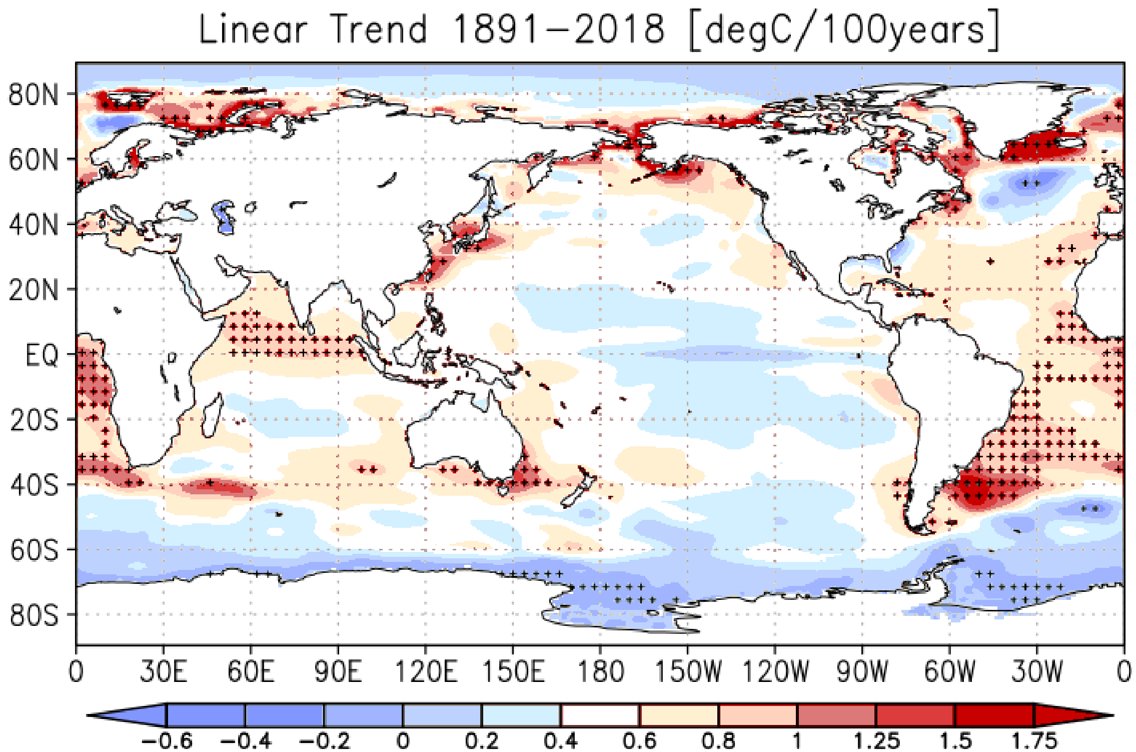
Surface temperature
Land

Surface temperature
Ocean

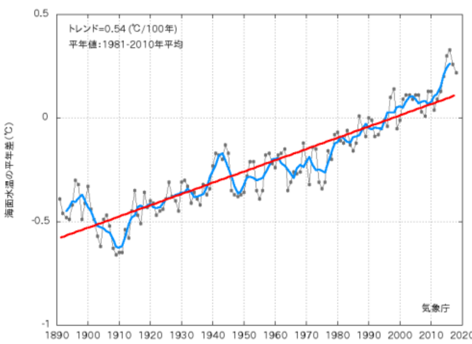
PDO
Pacific Decadal Oscillation

AMO
Atlantic Multi decadal Oscillation

Distribution of global warming rate
- refer to the global mean rate 0.54° C/100 year



0.54° C/100 year

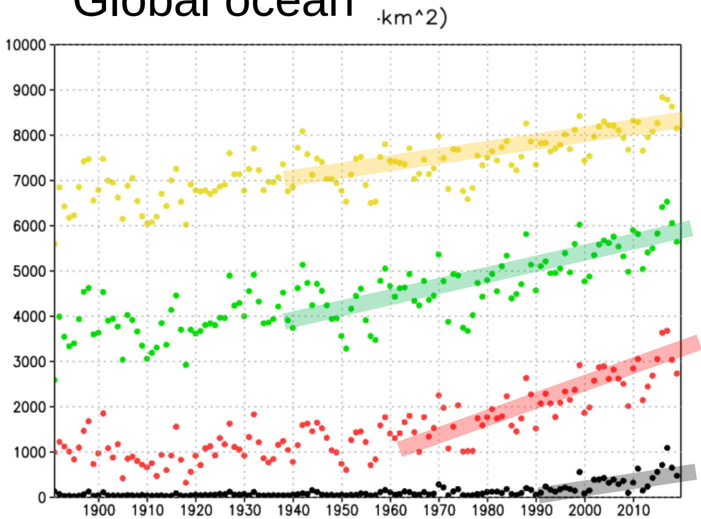


Long term variabilities of Warm pool SSTs

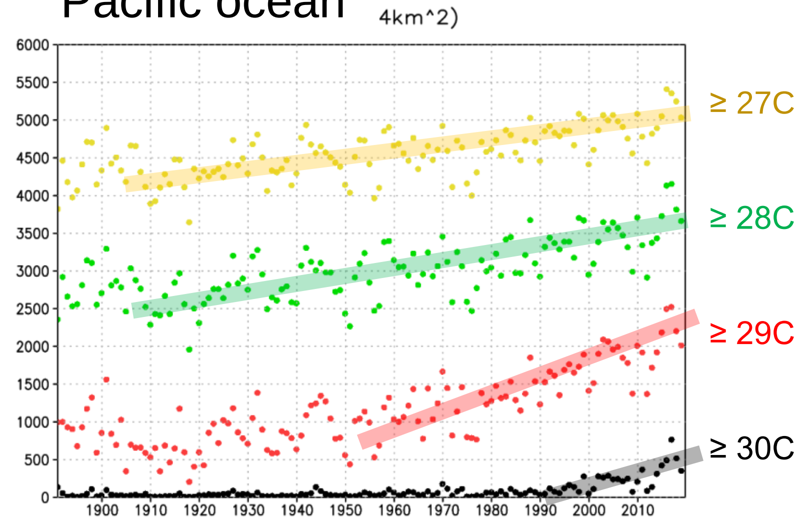
Yellow: Green: Red: Black:

area of SSTs ≥ 27C: ≥ 28C: ≥ 29C: ≥ 30C:

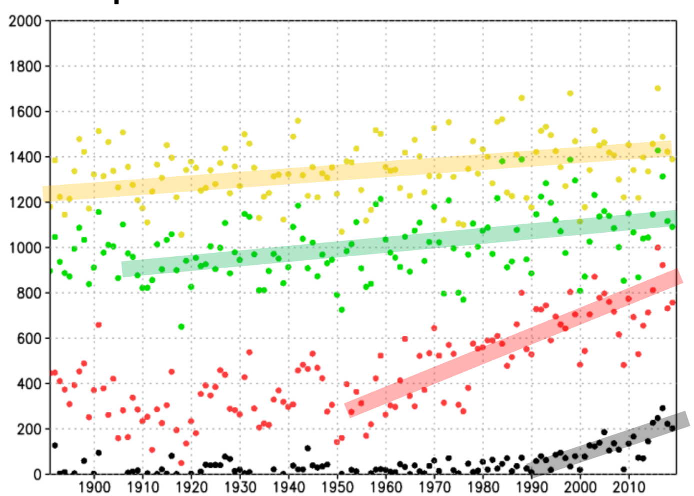
Global ocean



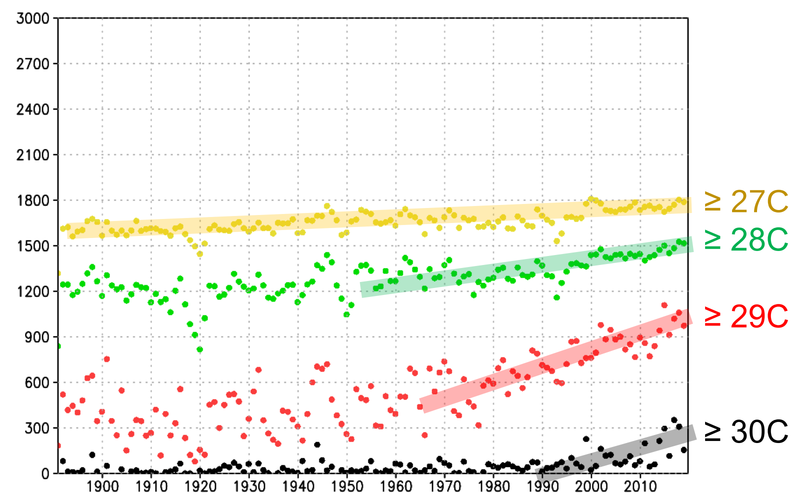
Pacific ocean



Equatorial Pacific ocean



Western North Pacific ocean



Thank you for your attention