

An aerial photograph of a vast, snow-covered mountain range. The peaks are rugged and partially obscured by soft, white clouds. A deep valley is visible in the foreground, with a winding road or path cutting through the snow. The overall scene is serene and majestic, with a cool color palette dominated by whites, blues, and greys.

Changes in North Pacific mixed layer depth in the 20th and 21st Centuries as simulated by coupled climate models

Bill Merryfield and Seulji Kwon

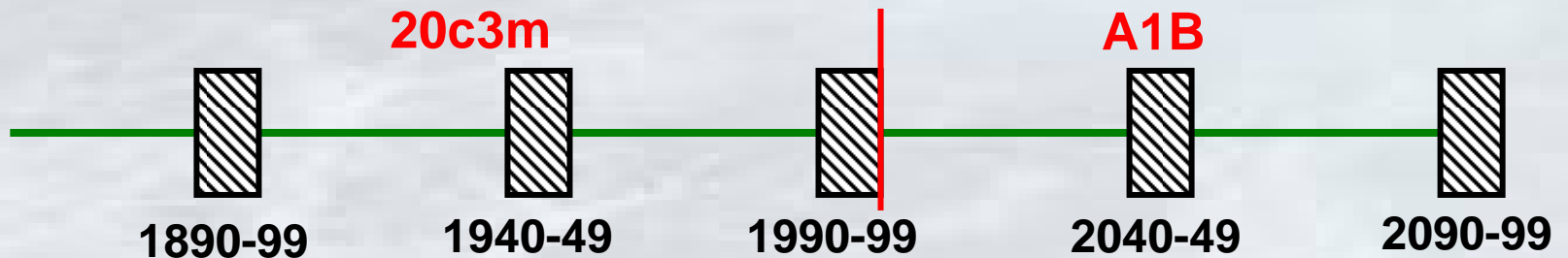
*Canadian Centre for Climate Modelling
and Analysis/Environment Canada*

Potential Impact of Mixed-Layer Depth Changes

- Depth of ocean mixed layer affects
 - volume of ocean in contact with atmosphere → rate of *ocean uptake of heat, CO₂*
 - *nutrient flux* from deep ocean
 - amount of *light* available for photosynthetic organisms
- Changes in mixed layer depth under anthropogenic warming can
 - act as a climate *feedback*
 - alter ocean ecosystems
- Have such changes already been observed?

Methodology

- Consider *climate model ensemble* assembled for IPCC AR4 (“*WCRP CMIP3 multi-model dataset*”)
- 17 Models, *20c3m Scenario* for 20th Century
A1B Scenario for 21st Century
- MLD algorithm of Kara et al. (JGR 2000)
- Construct monthly climatologies for *5 time slices*:



- Interpolate to common $3^{\circ} \times 3^{\circ}$ grid

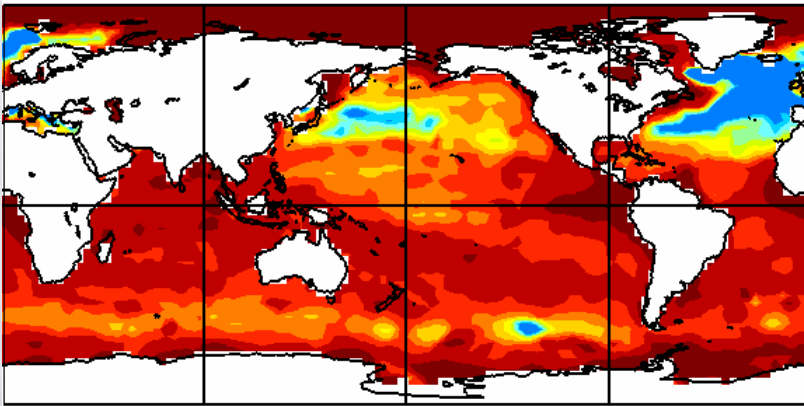
Multi-model ensemble

centre	model	country
BCCR	BCM2.0	Norway
Bonn/KMA	ECHO-G	Ger/Kor
CCCma	CGCM3.1(T63)	Canada
CCSR	MIROC3.2medres	Japan
CNRM	CM3	France
CSIRO	Mk3.0	Australia
GFDL	CM2.0	USA
GFDL	CM2.1	USA
GISS	AOM	USA
GISS	EH	USA
GISS	ER	USA
INGV	ECHAM4/OPA	Italy
IPSL	CM4	France
MPI	ECHAM5/OM	Germany
MRI	CGCM2.3.2	Japan
NCAR	CCSM3.0	USA
UKMO	HadCM3	UK

Present-day climatology

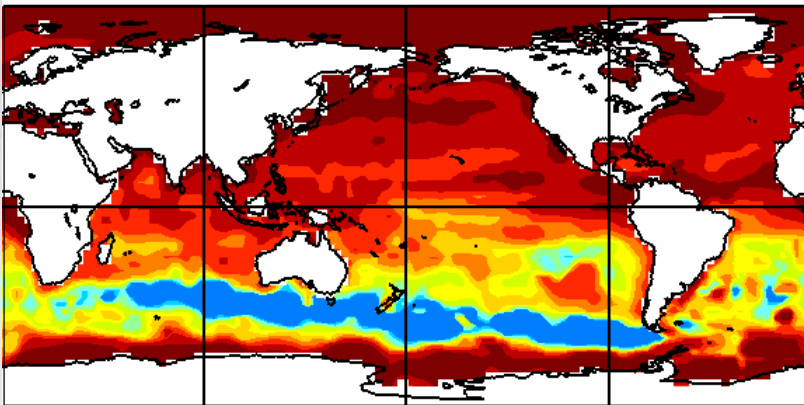
Observations: WOA/PHC

March

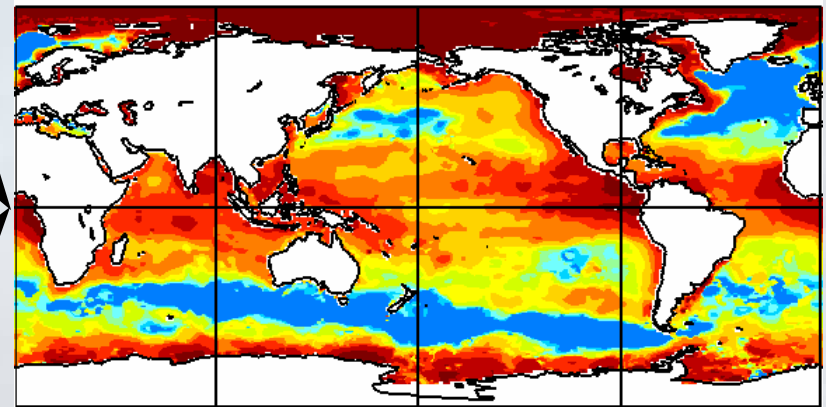


max of
annual
cycle

September



maxMLD



10 25 50 75 100 125 150 175 200 225 250

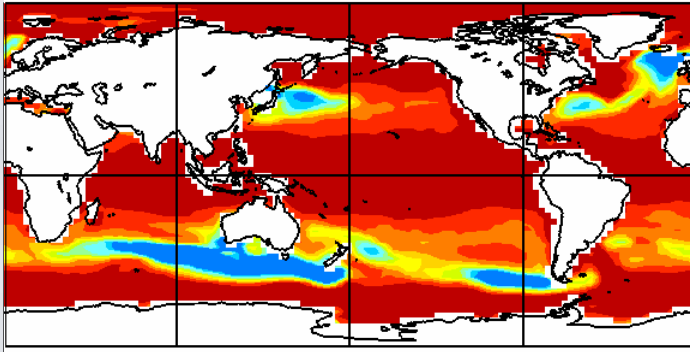
meters

10 25 50 75 100 125 150 175 200 225 250

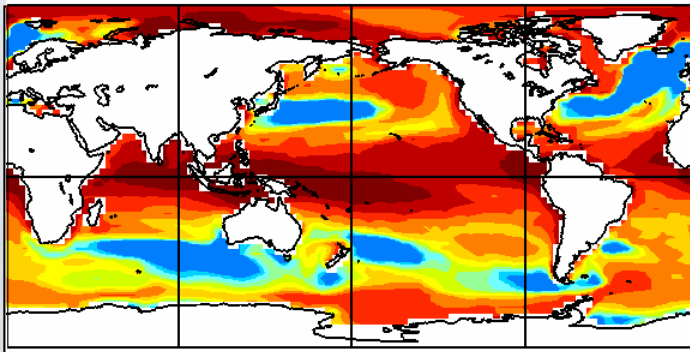
meters

Present-day maxMLD: models vs obs

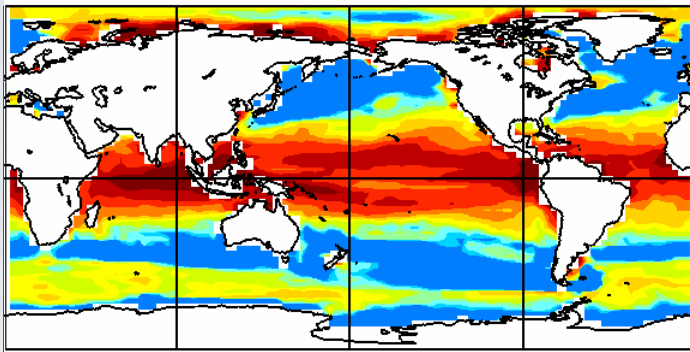
CCCma CGCM3.1(T63)



GFDL CM2.1

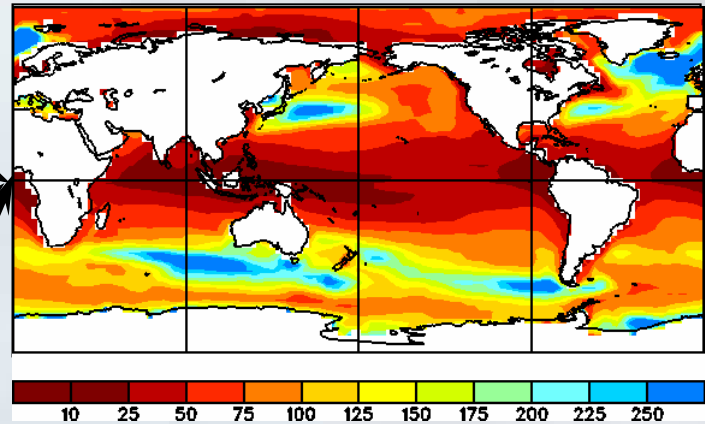


GISS AOM

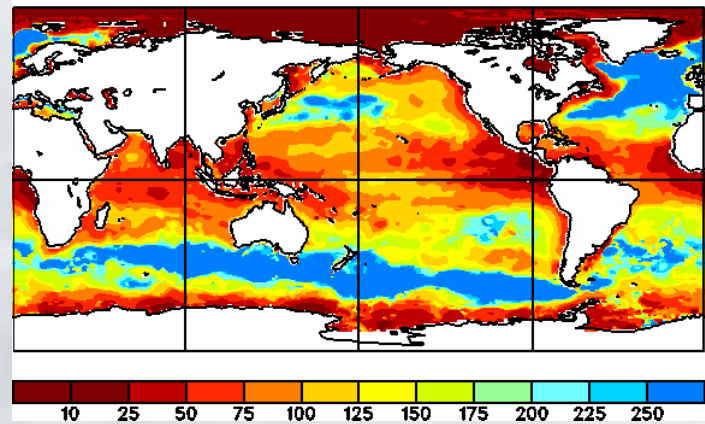


■ ■ ■

Geometric mean



WOA/PHC

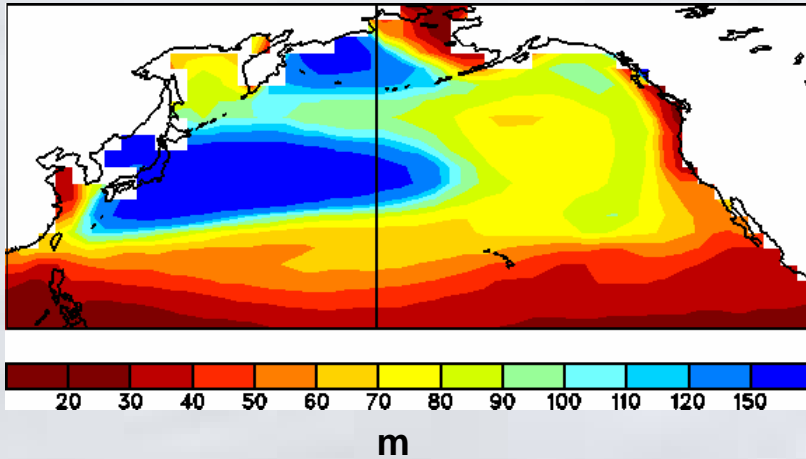


meters

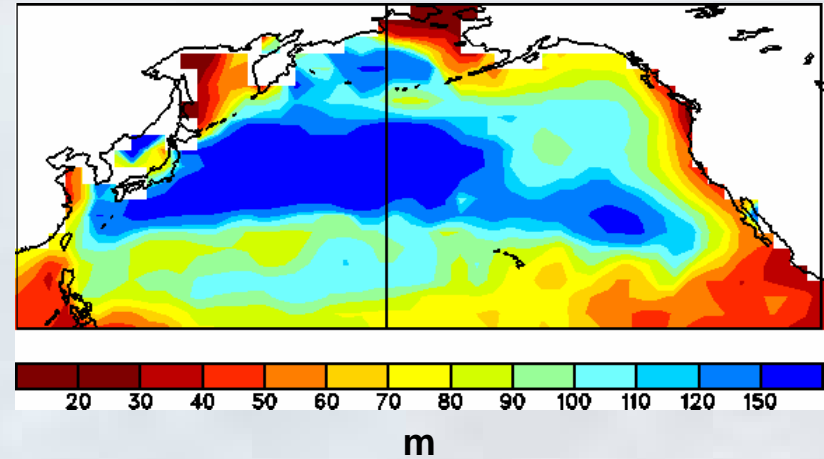
North Pacific maxMLD: models vs obs

1990-99

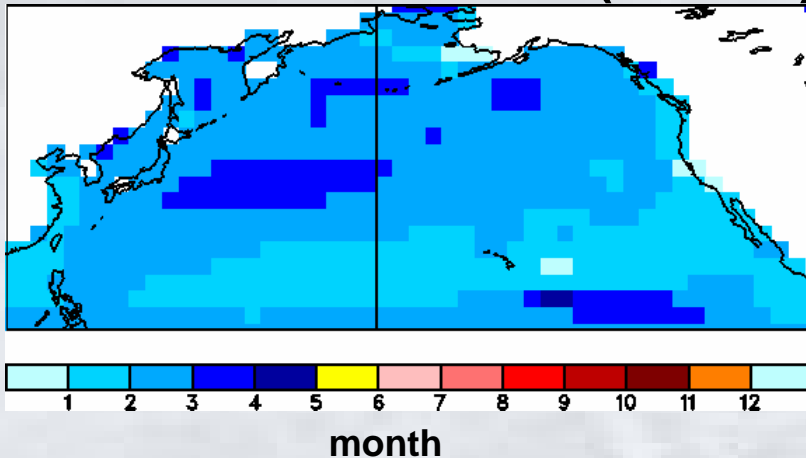
maxMLD (model geometric mean)



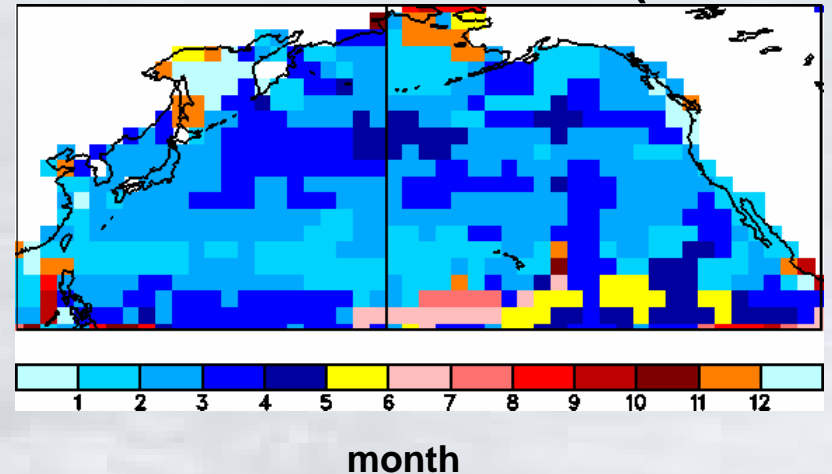
maxMLD (WOA/PHC)



mean month of maxMLD (models)



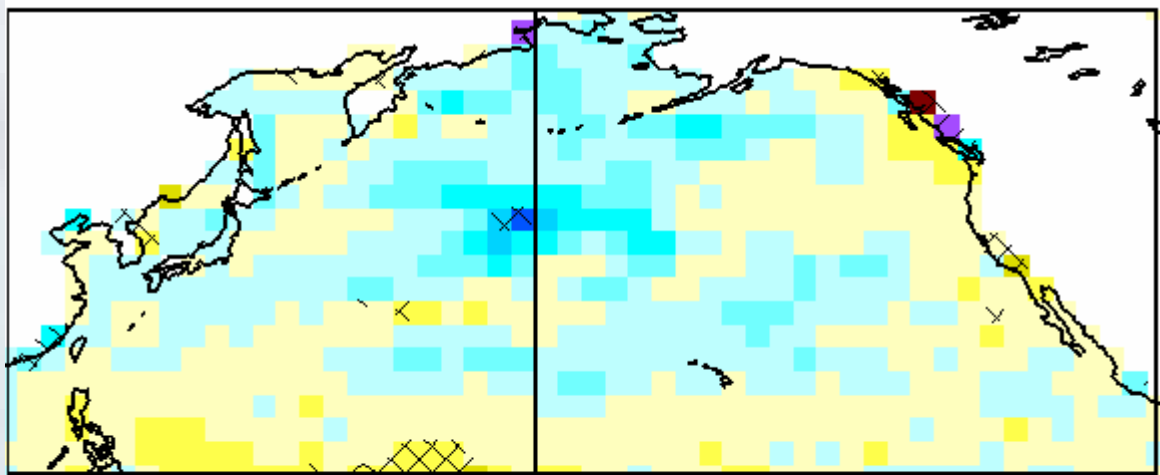
mean month of maxMLD (WOA/PHC)



Modeled 20th Century changes

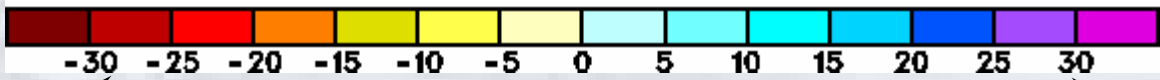
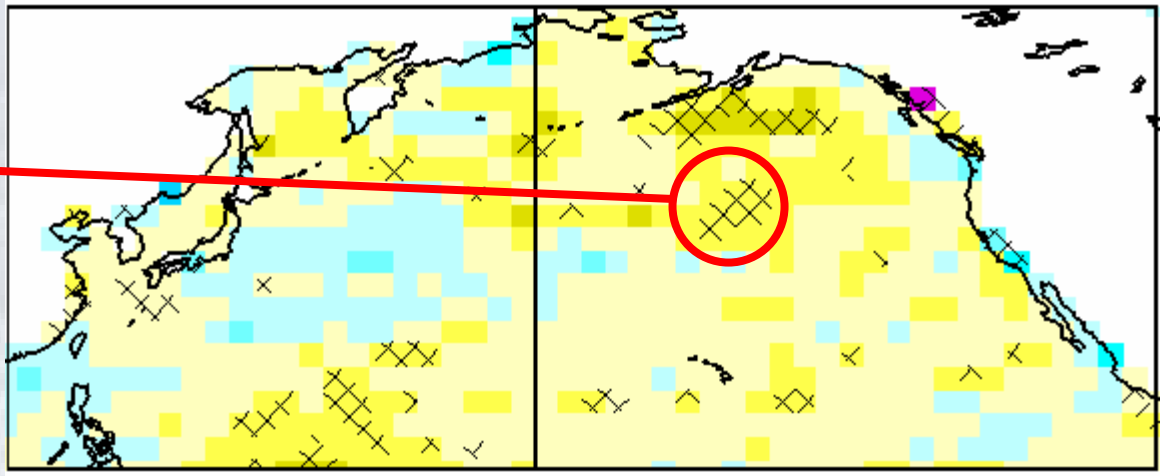
**Multi-model
mean Δ MLD**

(1940-49) – (1890-99)



Shading: >80% of
models agree on
sign of change
 $p \leq 1\%$

(1990-99) – (1940-49)

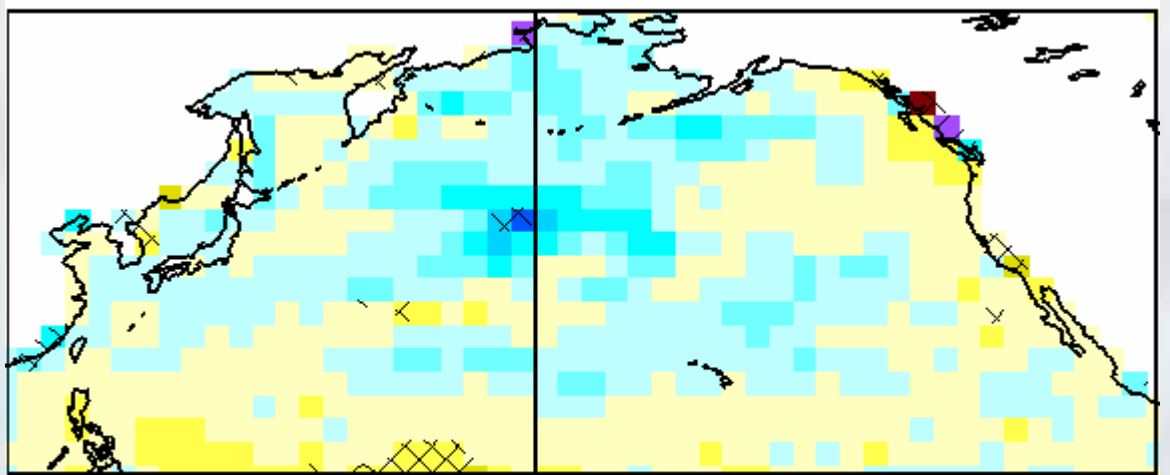


← **Shallowing** % change **Deepening** →

Modeled 20th Century changes

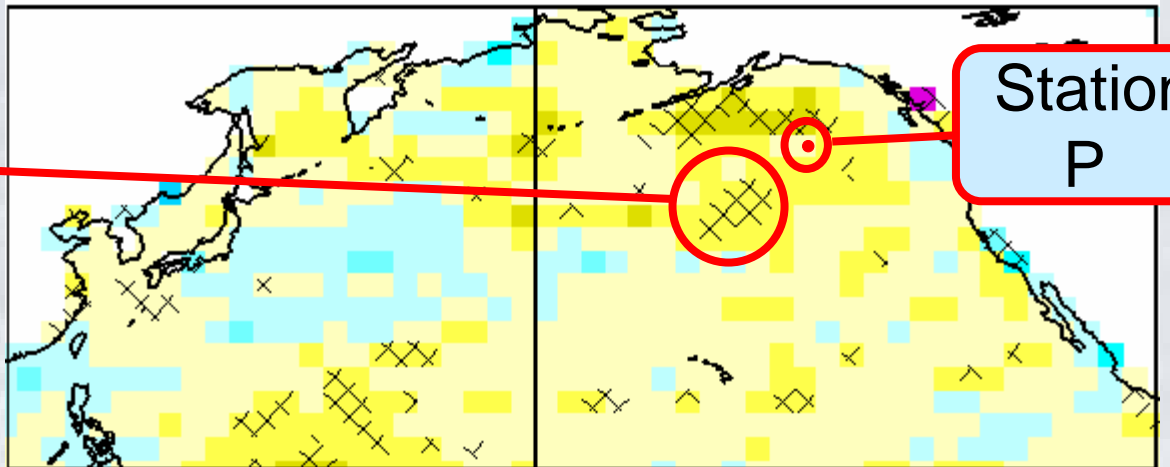
**Multi-model
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(1940-49) – (1890-99)

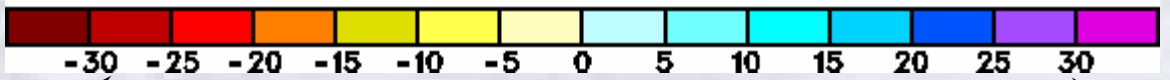


Shading: >80% of
models agree on
sign of change
 $p \leq 1\%$

(1990-99) – (1940-49)

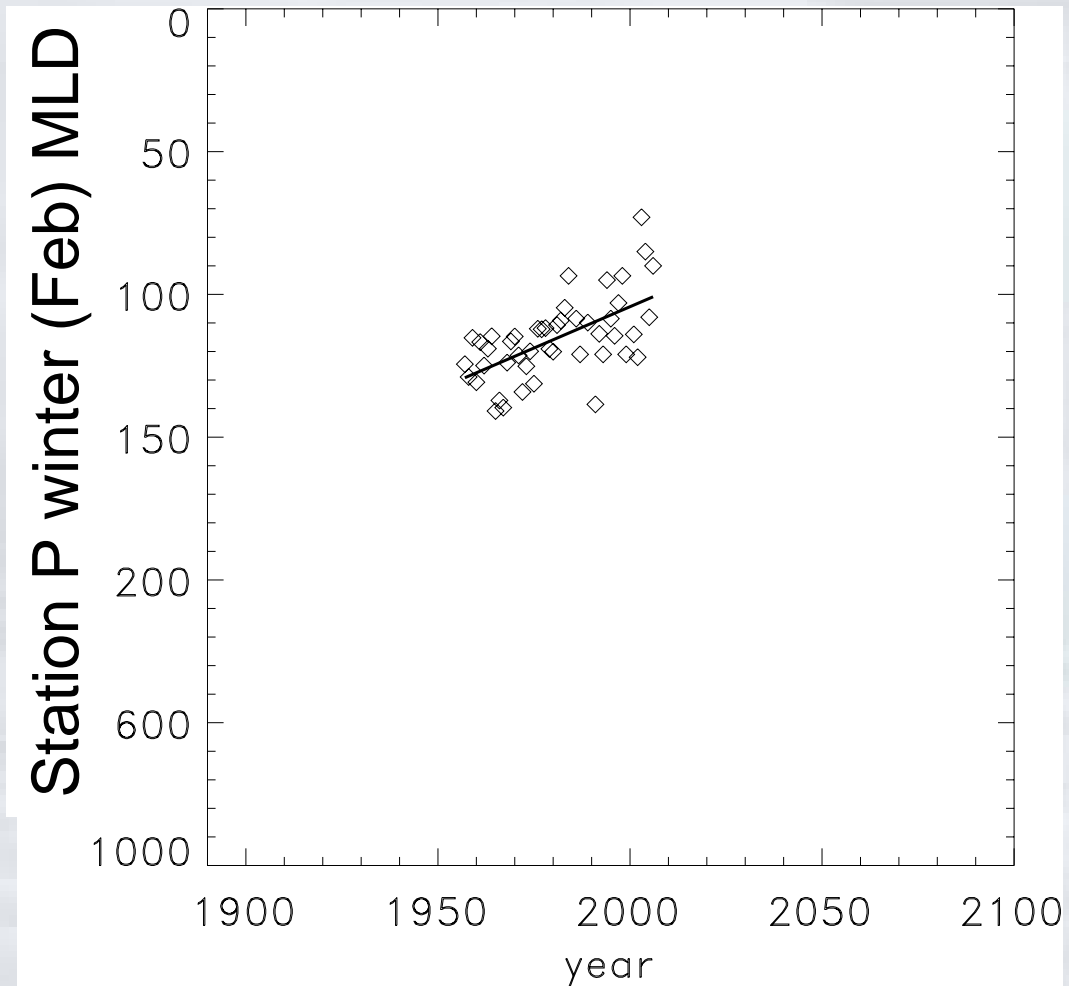


**Station
P**



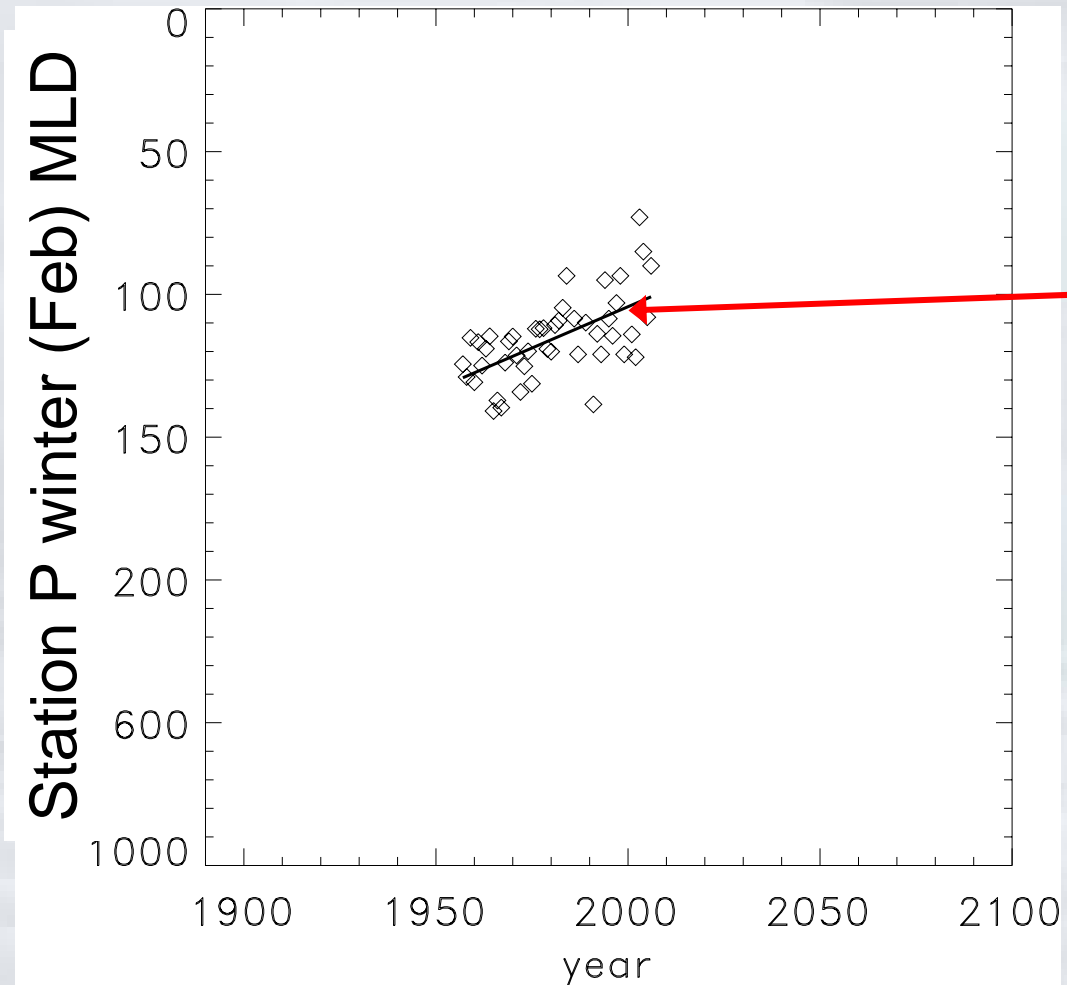
← **Shallowing** % change **Deepening** →

Station P time series 1956-2006



Data courtesy of
H. Freeland (IOS)

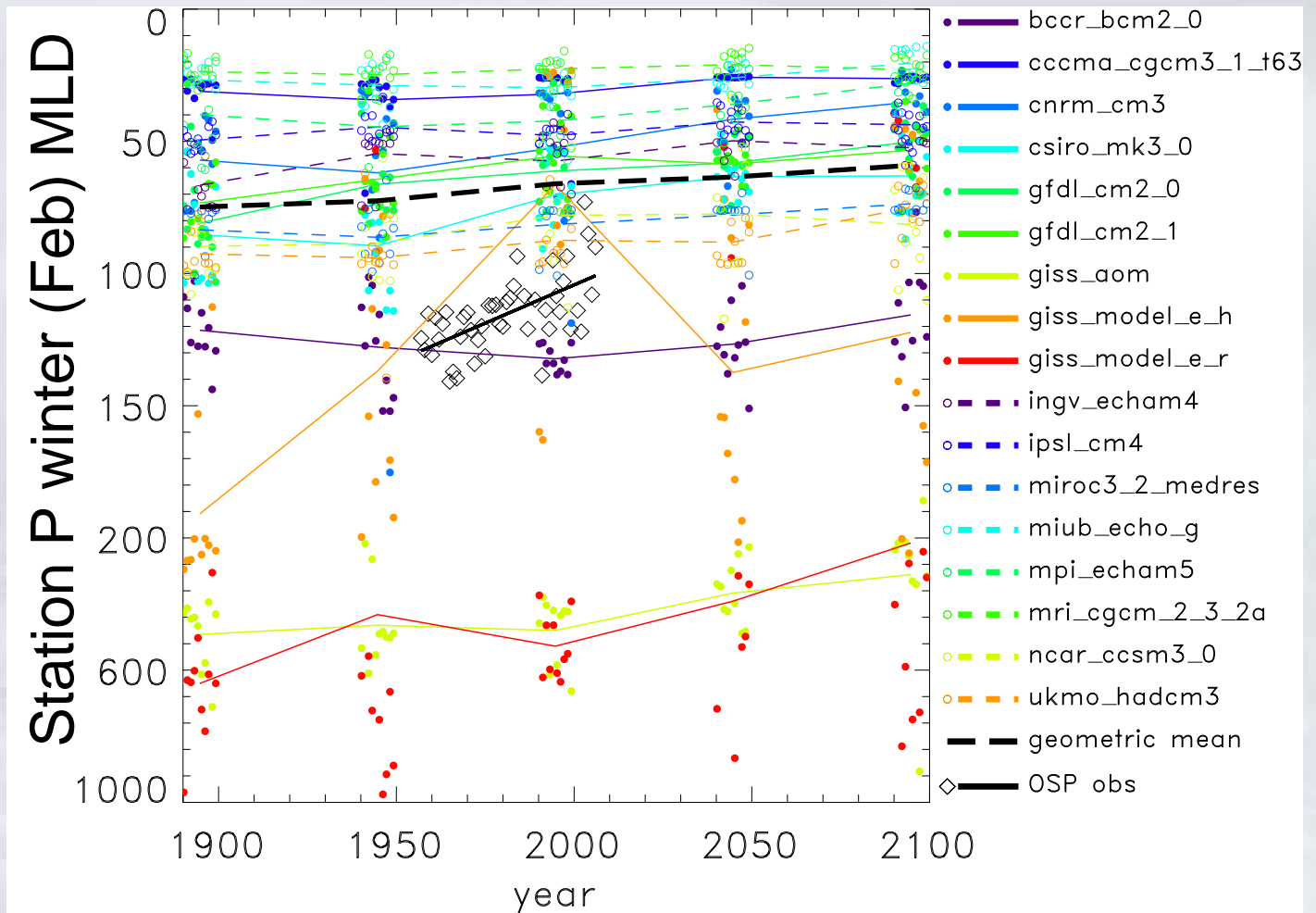
Station P time series 1956-2006



Trend: ML shallowing at $\approx 60\text{m/century}$

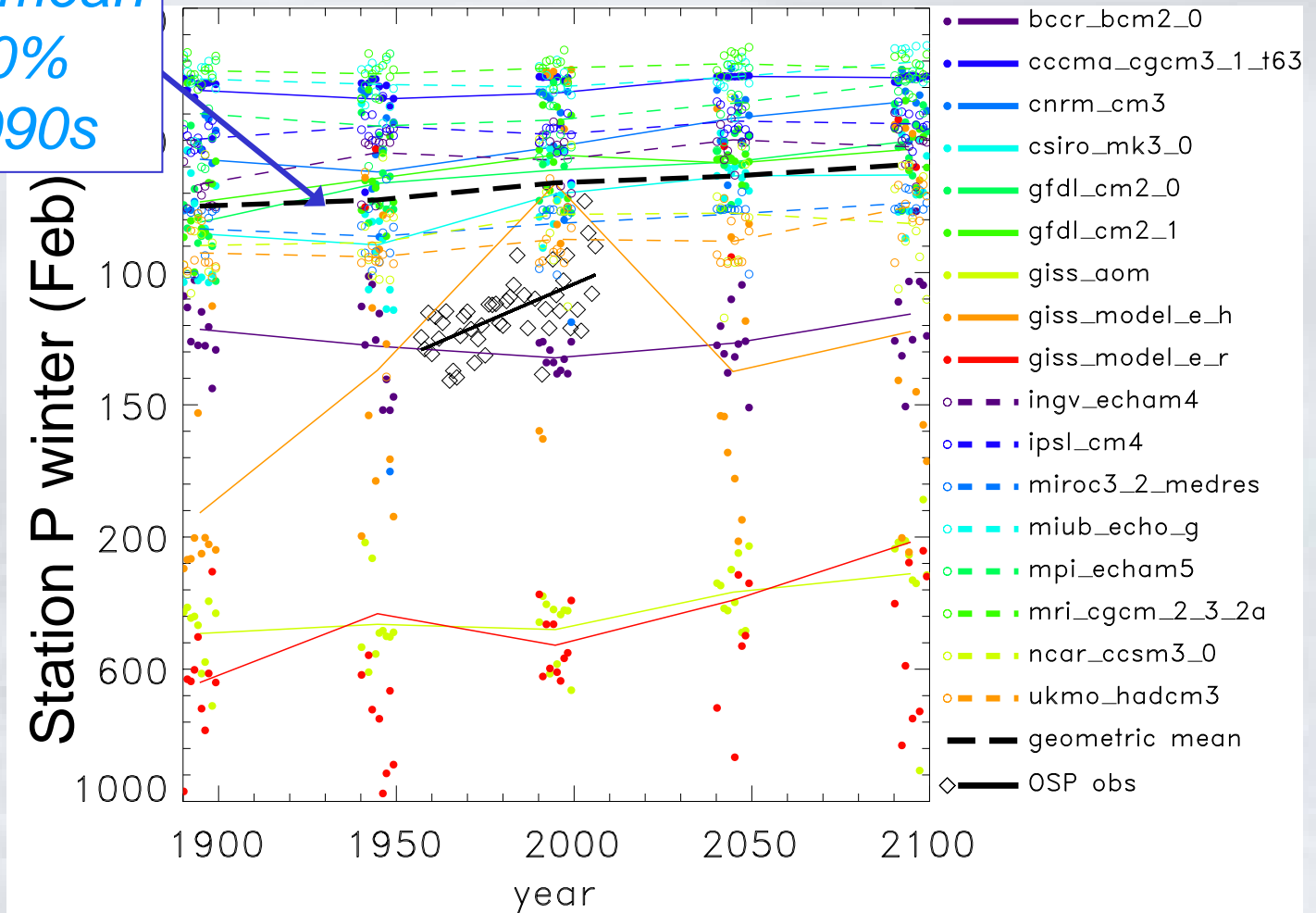
Data courtesy of H. Freeland (IOS)

Station P Observations vs Models

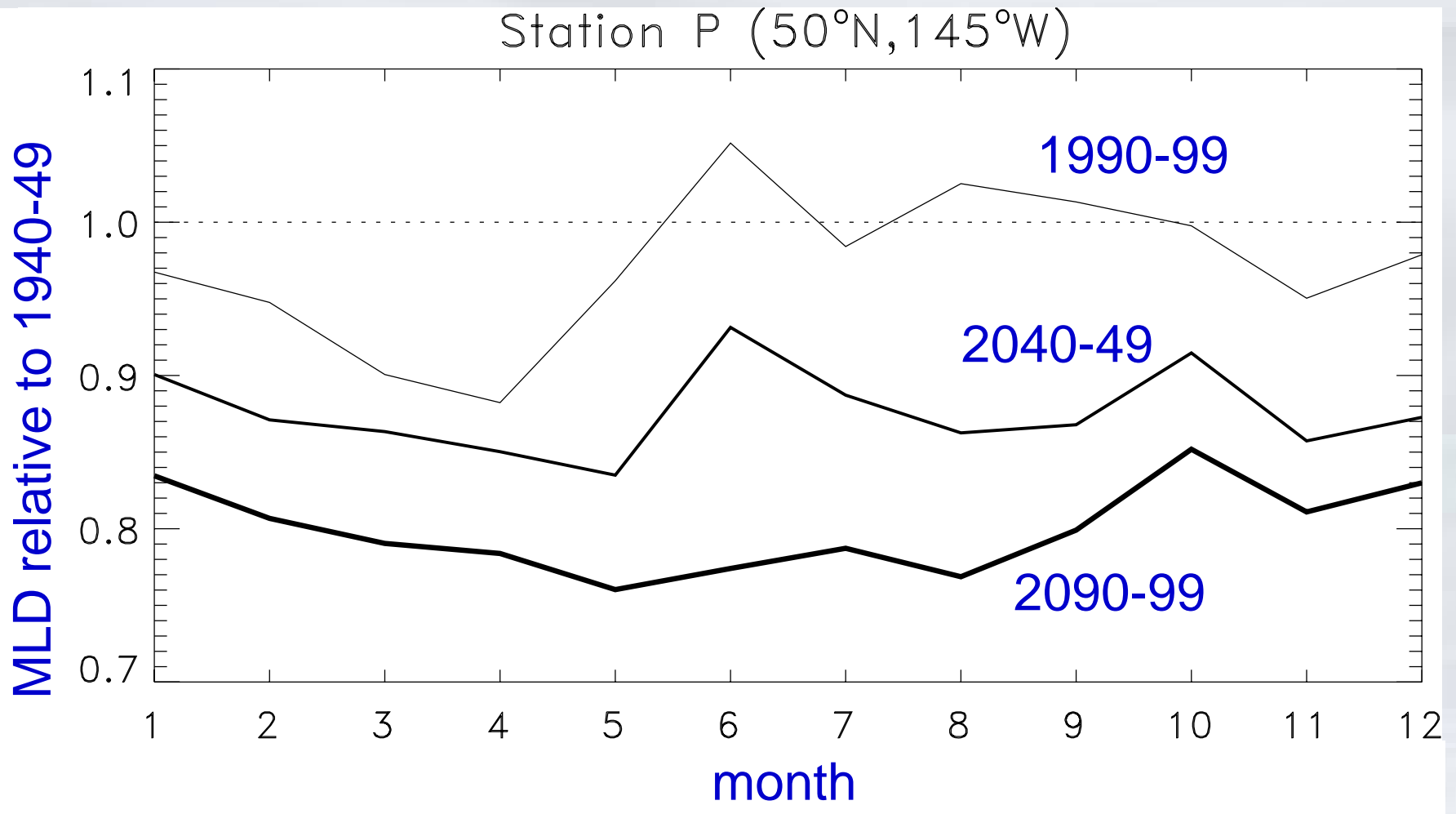


Station P Observations vs Models

Geometric mean
decr ~20%
1940s-2090s



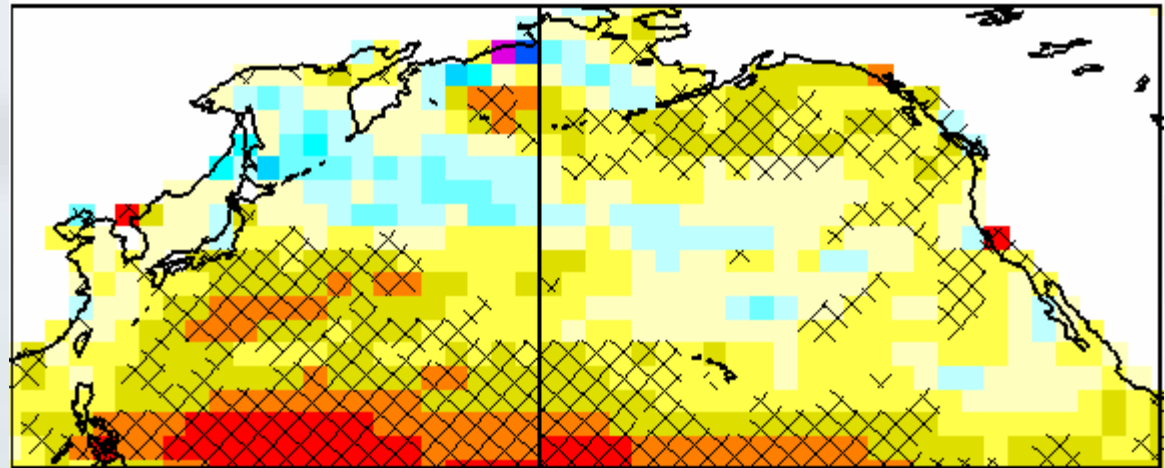
Projected seasonal changes



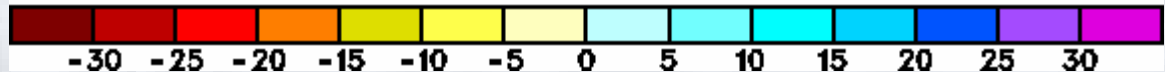
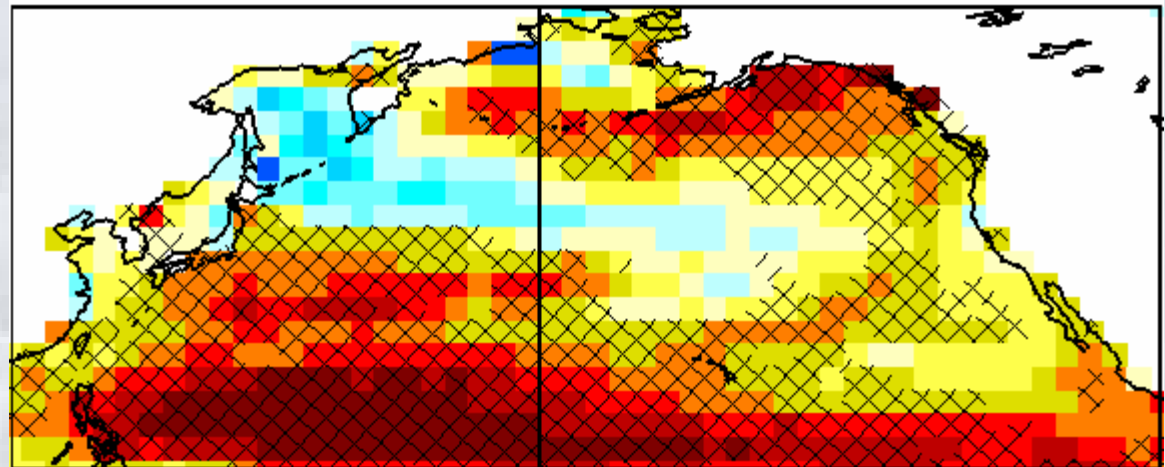
Projected 21st Century Changes

**Multi-model
mean Δ MLD**

(2040-49) – (1990-99)



(2090-99) – (1990-99)



← **Shallowing** % change **Deepening** →

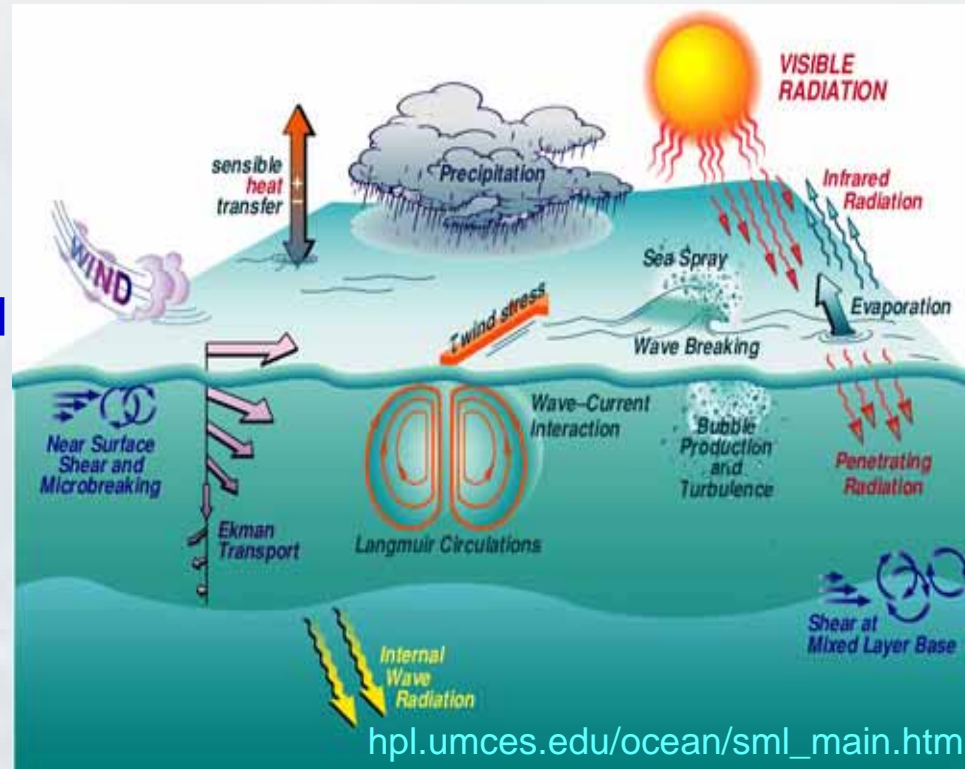
Processes affecting MLD

ML *deepened* by

- surface densification
- mech energy input from wind

ML deepening *resisted* by

- upper ocean stratification



∴ ML will tend to *shallow* under

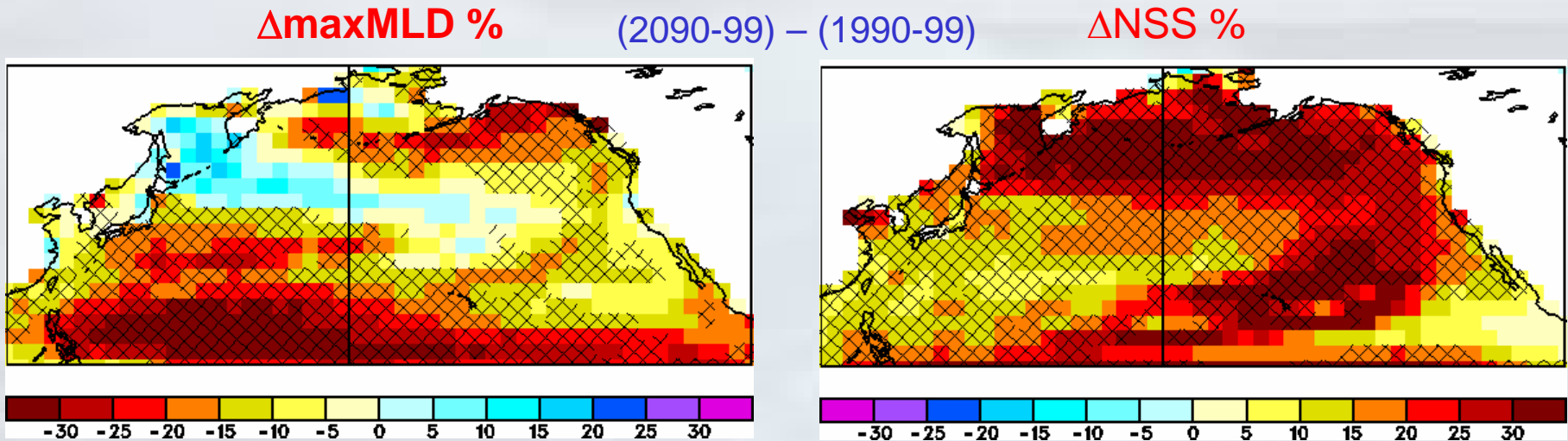
- increased upper ocean stratification
- decreased surface wind speed
- decreased winter cooling

← surface warming

← surface freshening

Attribution of 21st Century Changes

changes in maxMLD vs upper ocean stratification:



**NSS = near surface stratification
(max of seasonal cycle)**

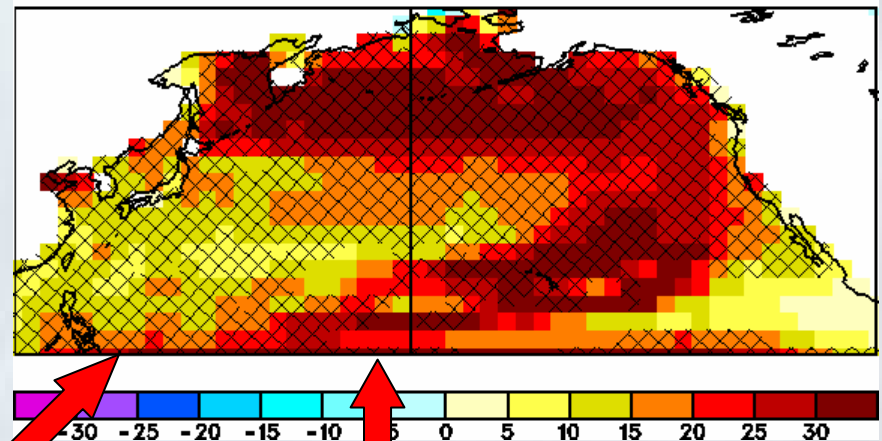
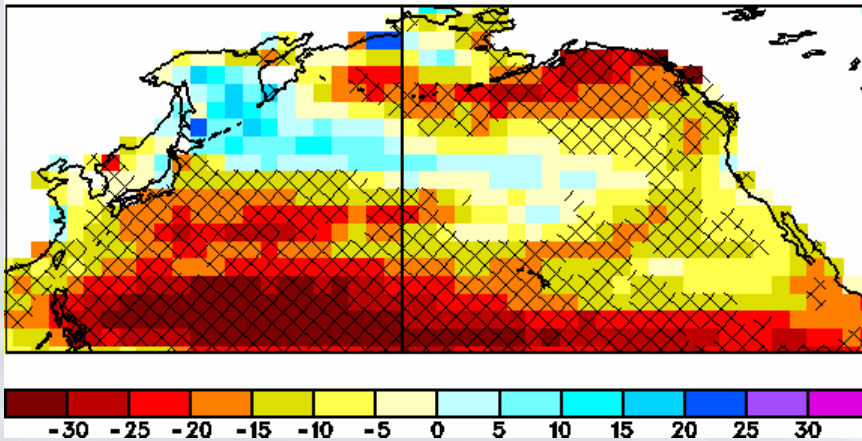
Attribution of 21st Century Changes

changes in maxMLD vs upper ocean stratification:

Δ maxMLD %

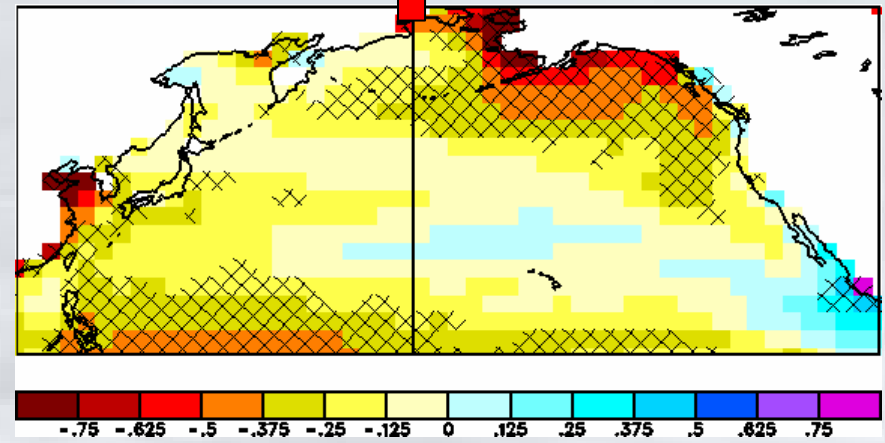
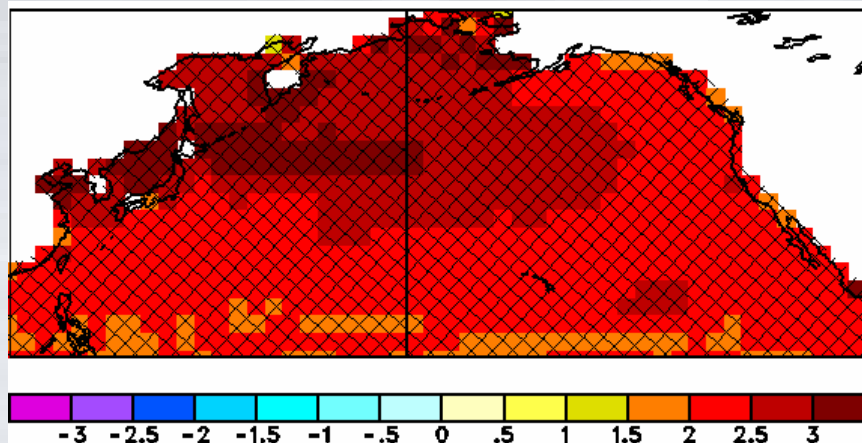
(2090-99) – (1990-99)

Δ NSS %



Δ SST in month of max NSS ($^{\circ}$ C)

Δ SSS in month of max NSS (psu)



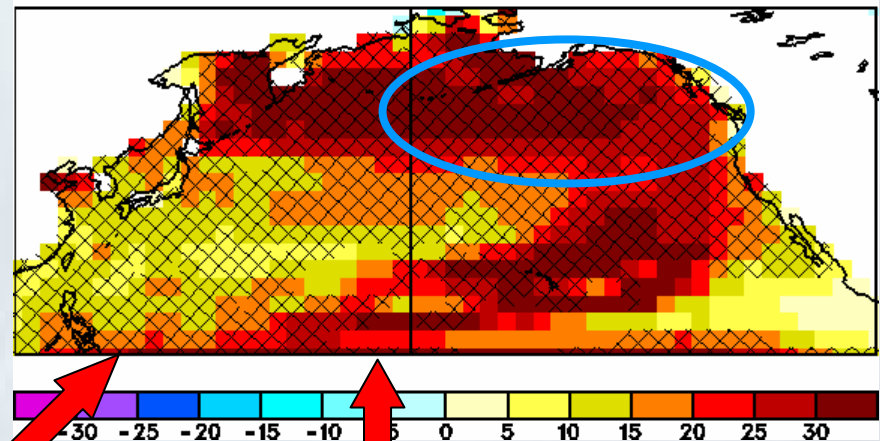
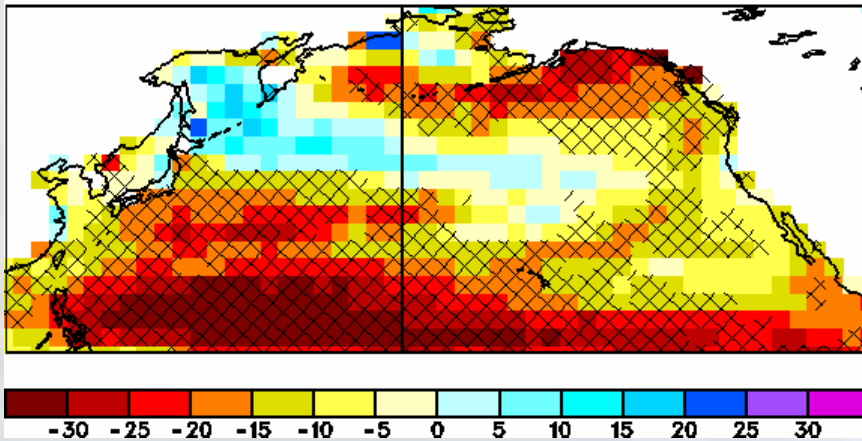
Attribution of 21st Century Changes

changes in maxMLD vs upper ocean stratification:

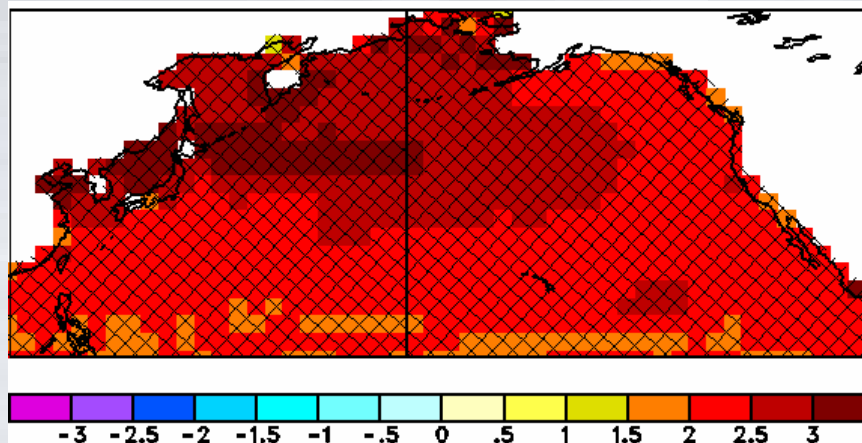
Δ maxMLD %

(2090-99) – (1990-99)

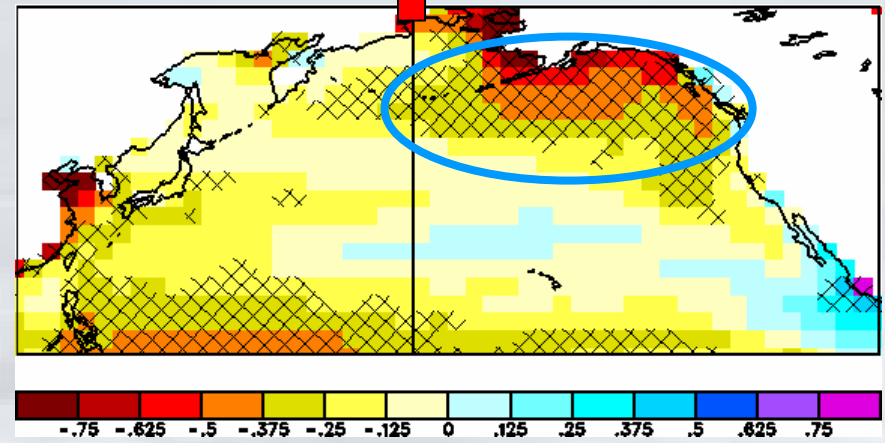
Δ NSS %



Δ SST in month of max NSS ($^{\circ}$ C)



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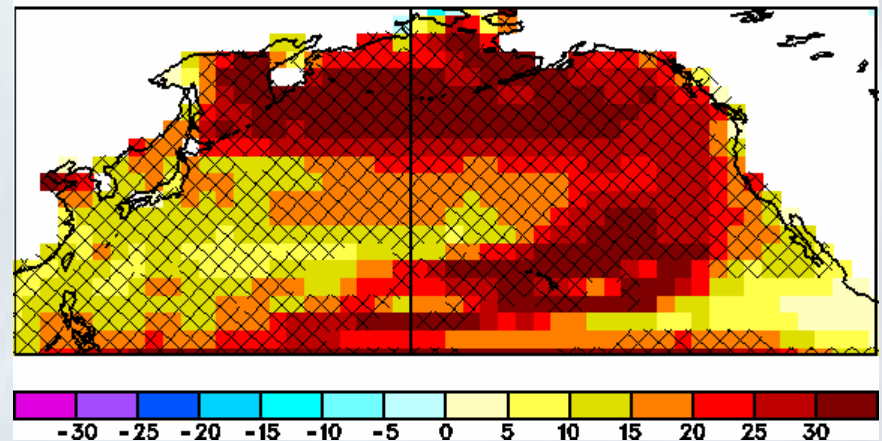
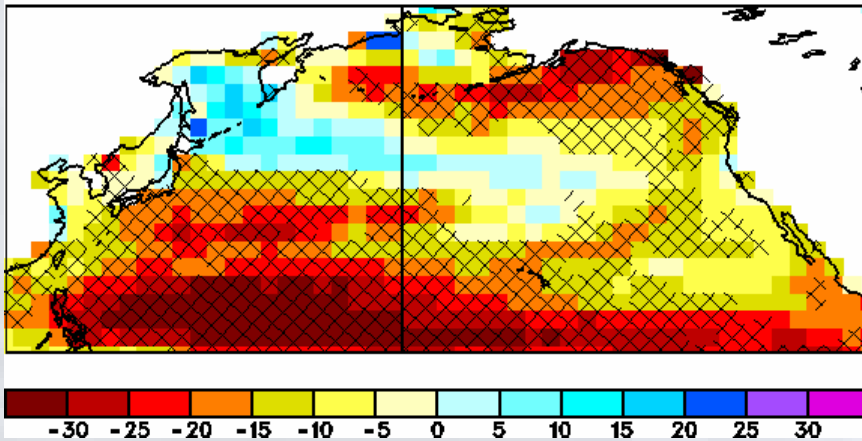
Attribution of 21st Century Changes

changes in maxMLD vs upper ocean stratification:

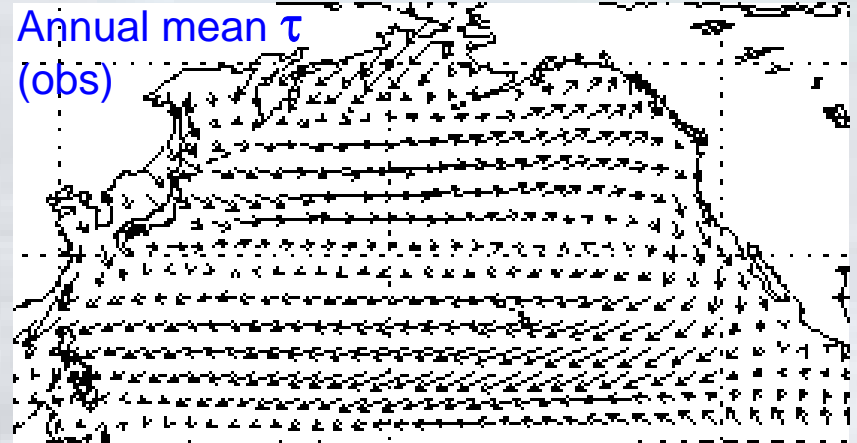
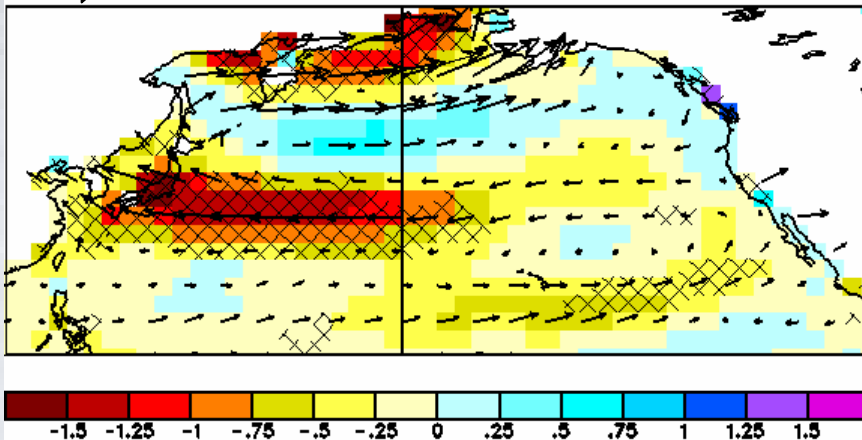
$\Delta \text{maxMLD} \%$

(2090-99) – (1990-99)

$\Delta \text{NSS} \%$



$\Delta(\text{annual mean } \tau, |\tau|) \text{ Nm}^{-2}$



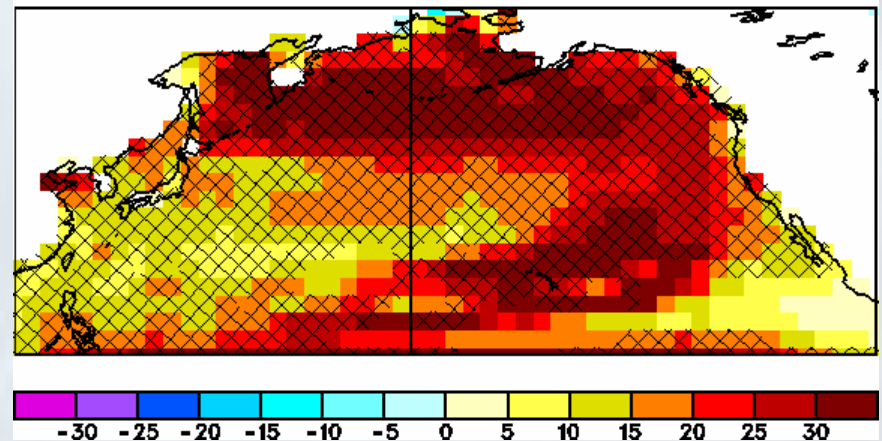
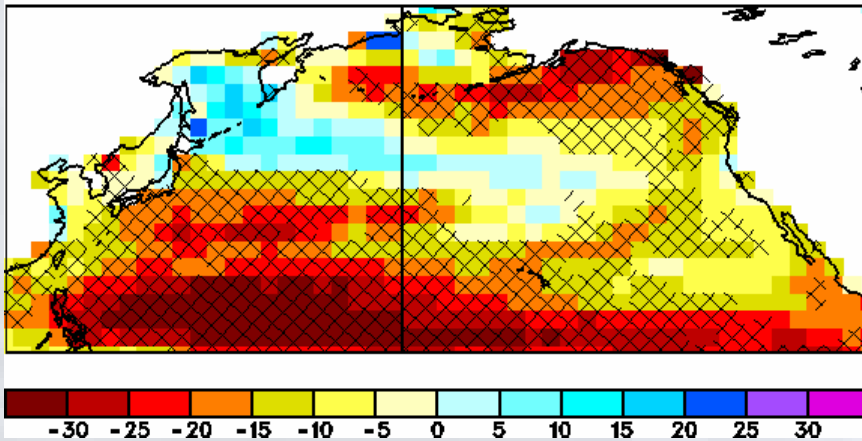
Attribution of 21st Century Changes

changes in maxMLD vs upper ocean stratification:

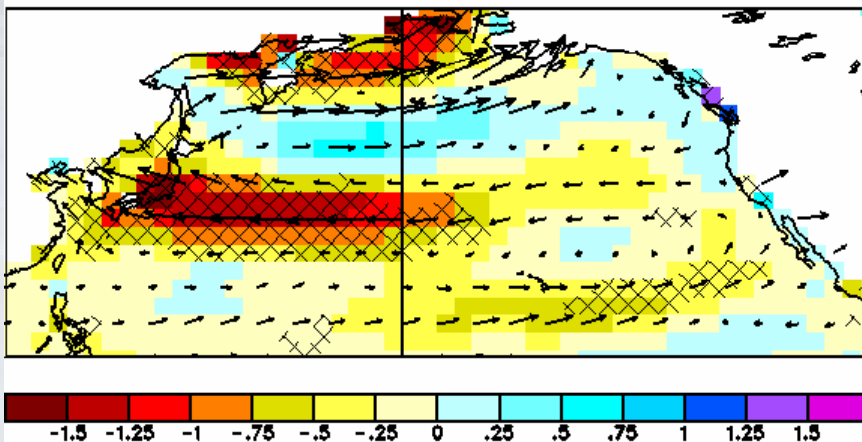
$\Delta \text{maxMLD} \%$

(2090-99) – (1990-99)

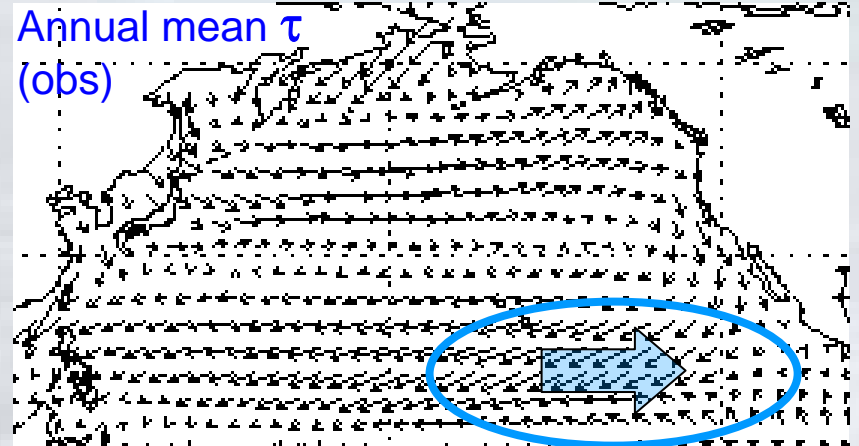
$\Delta \text{NSS} \%$



$\Delta(\text{annual mean } \vec{\tau}, |\tau|) \text{ Nm}^{-2}$



Annual mean τ
(obs)



trade winds weaken

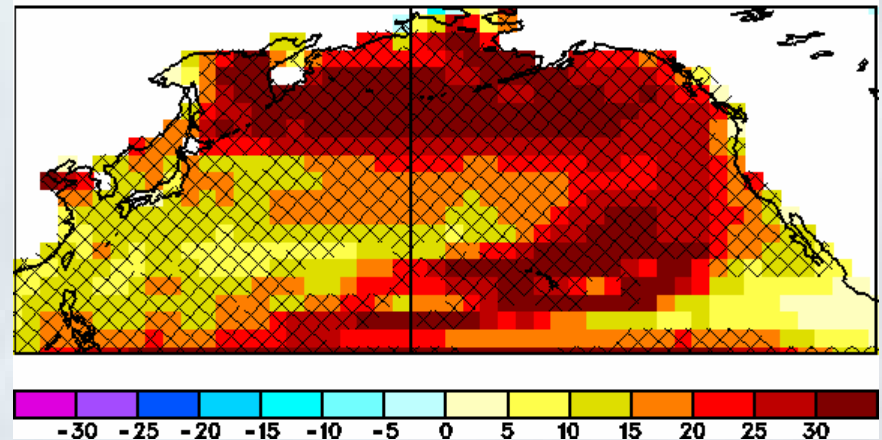
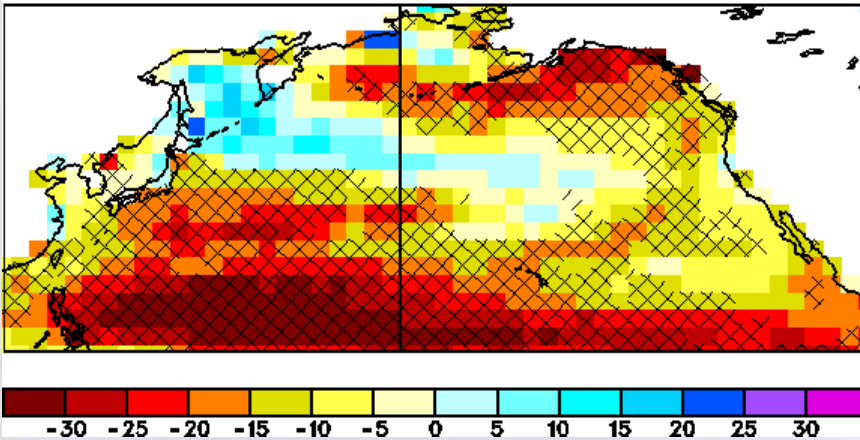
Attribution of 21st Century Changes

changes in maxMLD vs upper ocean stratification:

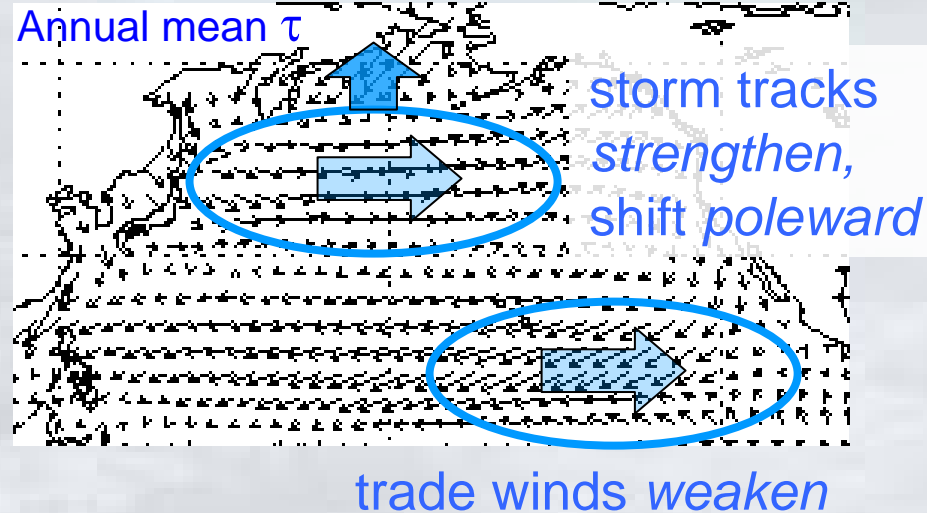
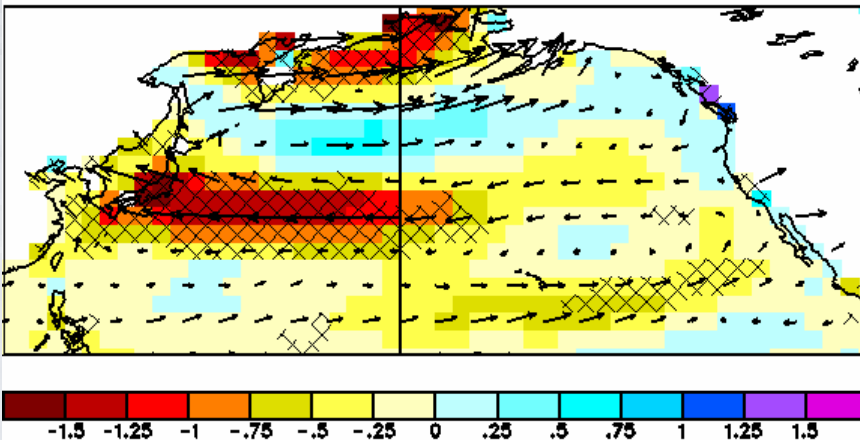
$\Delta \text{maxMLD} \%$

(2090-99) – (1990-99)

$\Delta \text{NSS} \%$



$\Delta(\text{annual mean } \vec{\tau}, |\tau|) \text{ Nm}^{-2}$



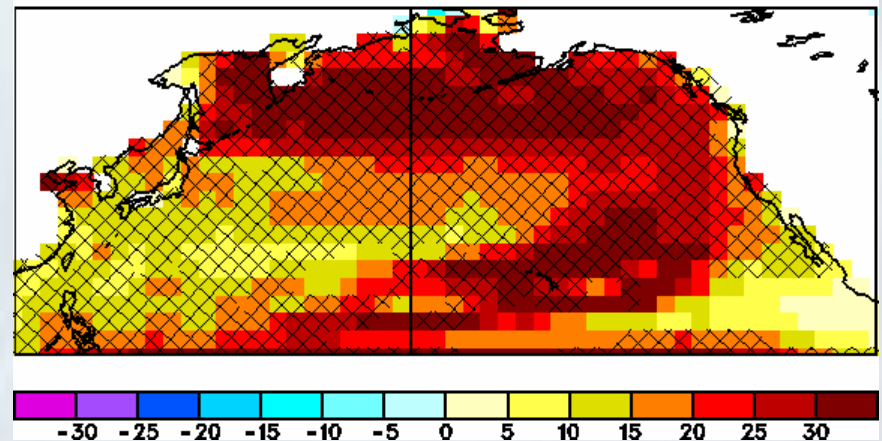
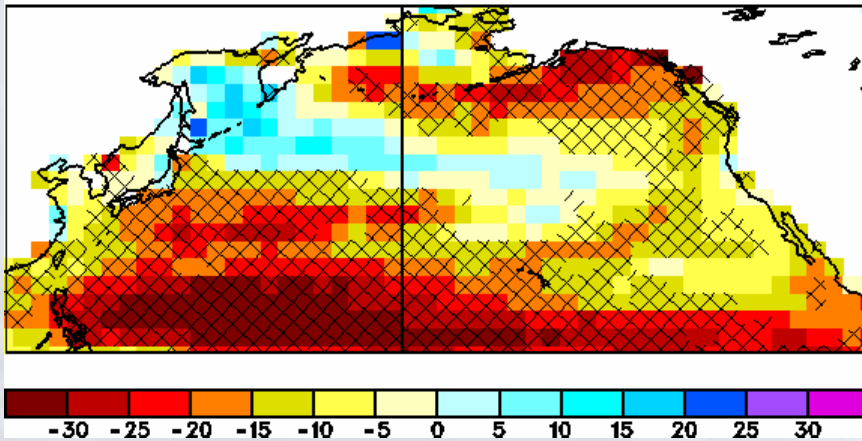
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changes in maxMLD vs upper ocean stratification:

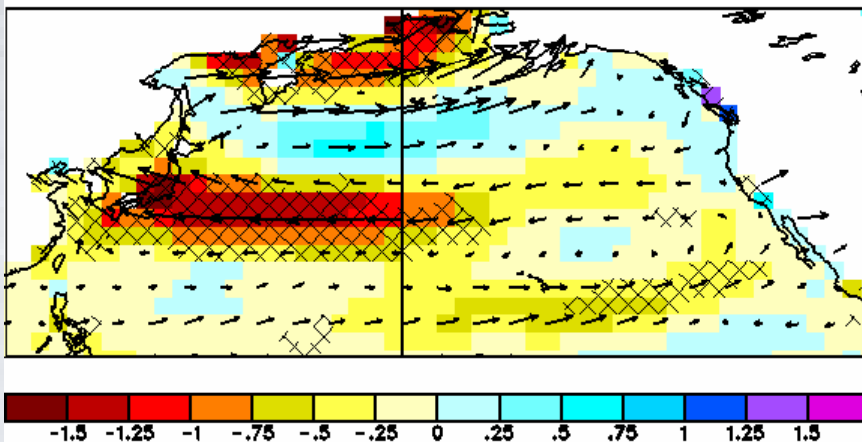
$\Delta \text{maxMLD} \%$

(2090-99) – (1990-99)

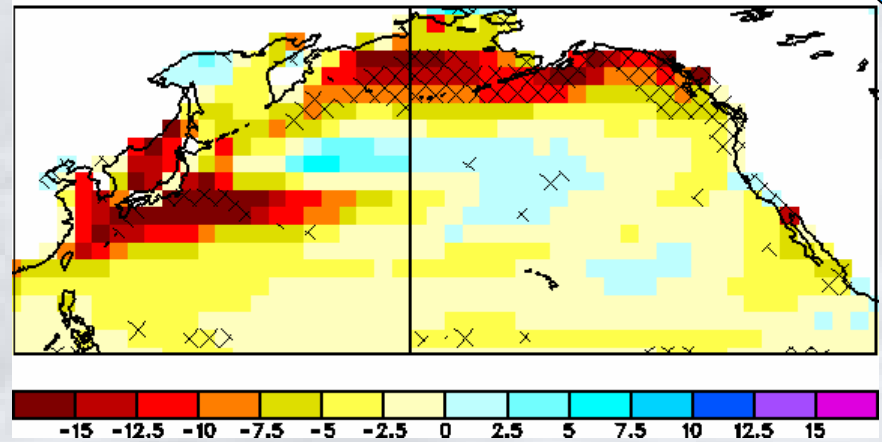
$\Delta \text{NSS} \%$



$\Delta(\text{annual mean } \vec{\tau}, |\tau|) \text{ Nm}^{-2}$



$\Delta(\text{ann mean surface cooling}) \text{ Wm}^{-2}$

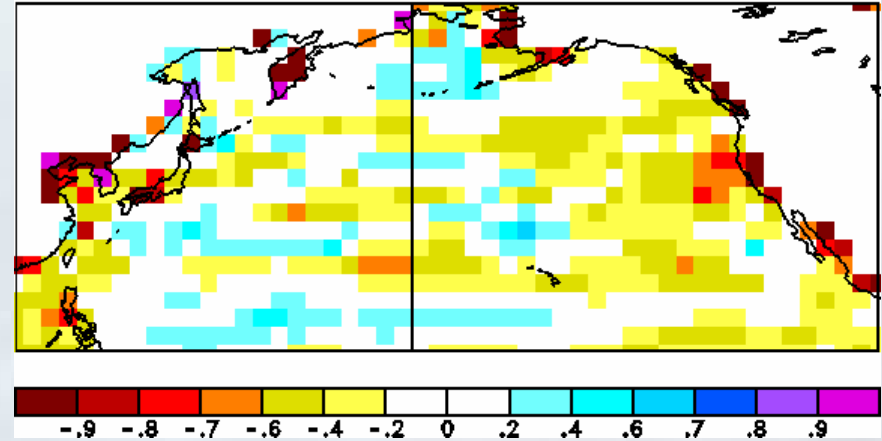
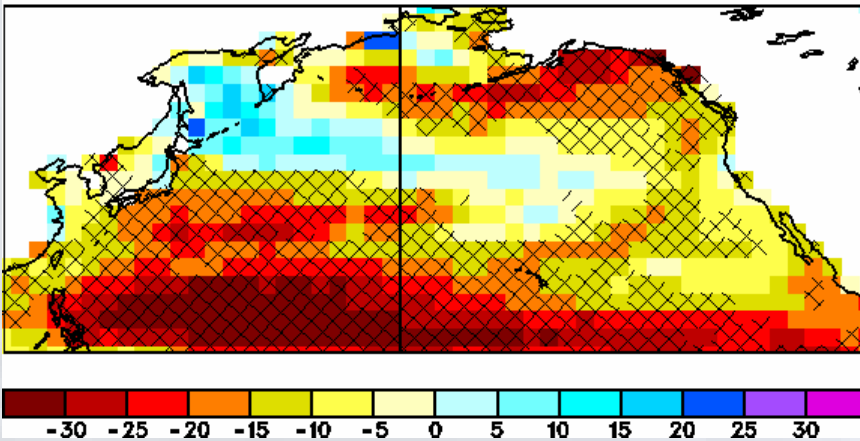


Attribution of 21st Century Changes

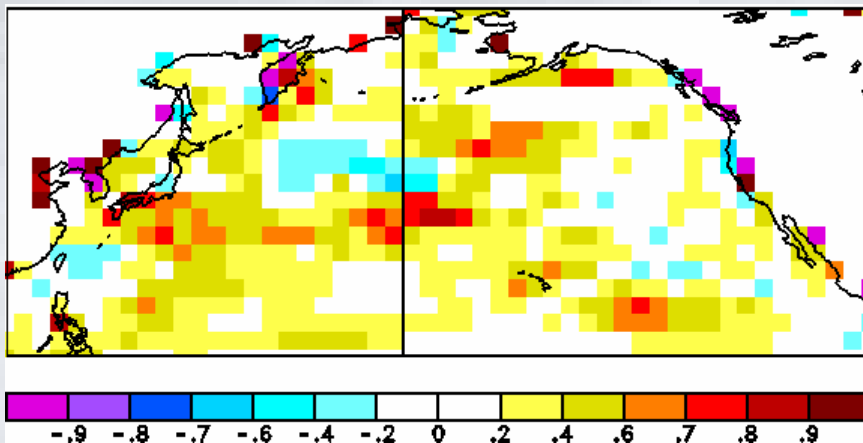
As a crude measure of causality, consider multimodel correlation of ΔmaxMLD vs ΔNSS , $\Delta|\tau|$, $\Delta\text{cooling}$

$\Delta\text{maxMLD} \%$

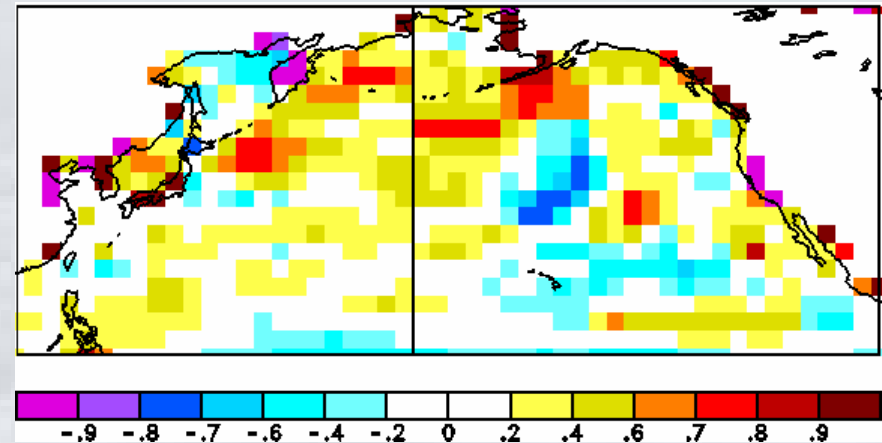
(2090-99) – (1990-99) $\text{corr}(\Delta\text{maxMLD}, \Delta\text{NSS})$



$\text{corr}(\Delta\text{maxMLD}, \Delta|\tau|)$



$\text{corr}(\Delta\text{maxMLD}, \Delta\text{cooling})$

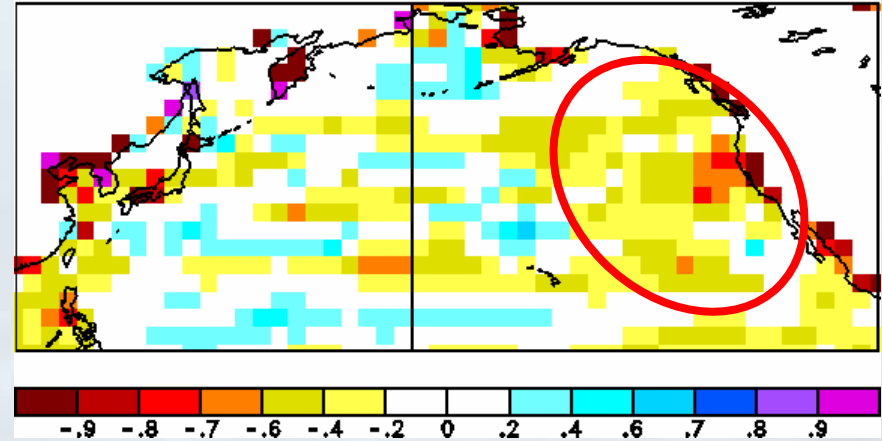
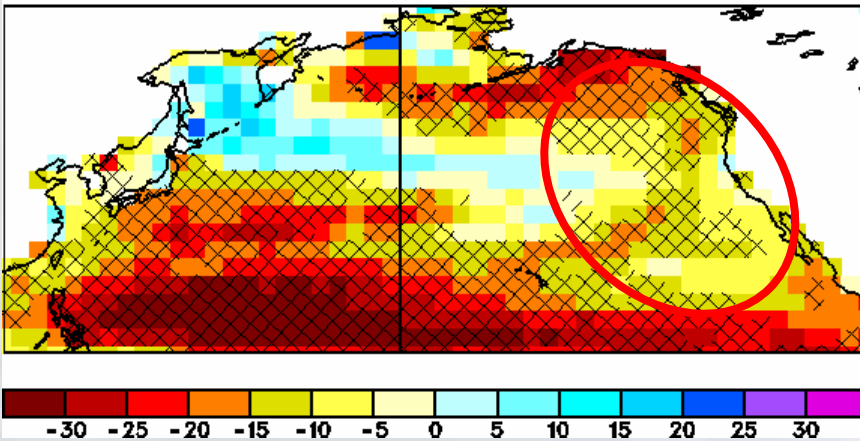


Attribution of 21st Century Changes

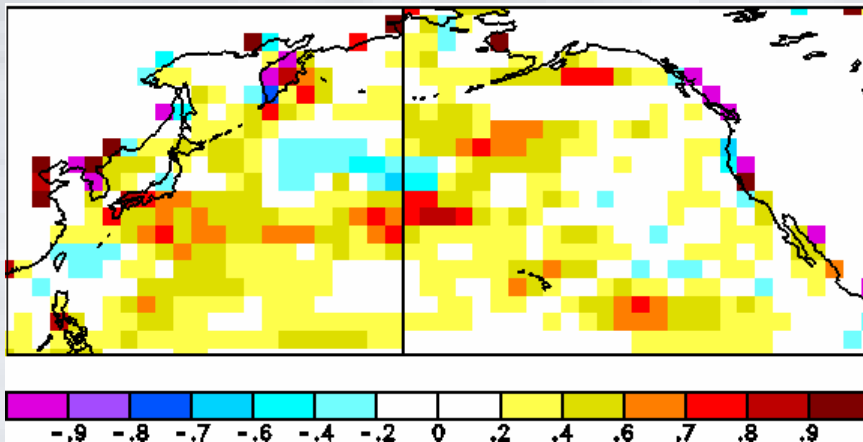
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ΔmaxMLD %

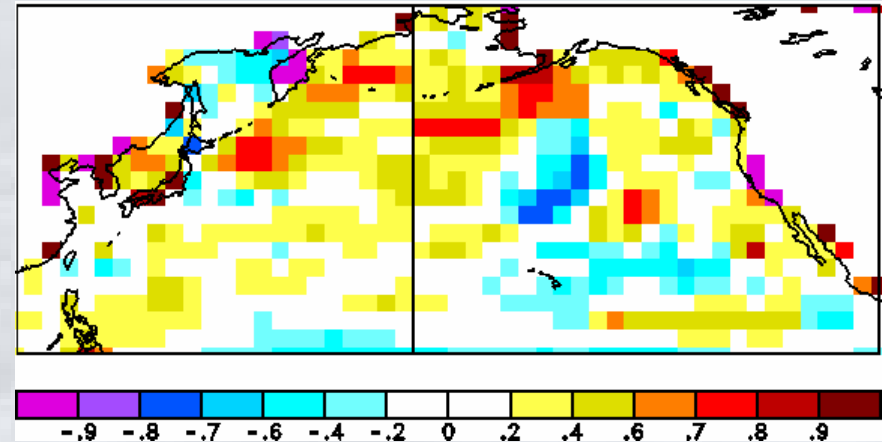
(2090-99) – (1990-99) $\text{corr}(\Delta\text{maxMLD}, \Delta\text{NSS})$



$\text{corr}(\Delta\text{maxMLD}, \Delta|\tau|)$



$\text{corr}(\Delta\text{maxMLD}, \Delta\text{cooling})$

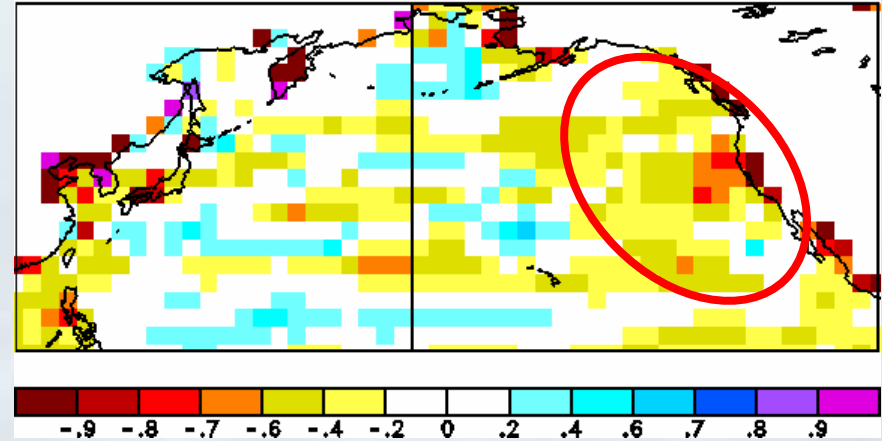
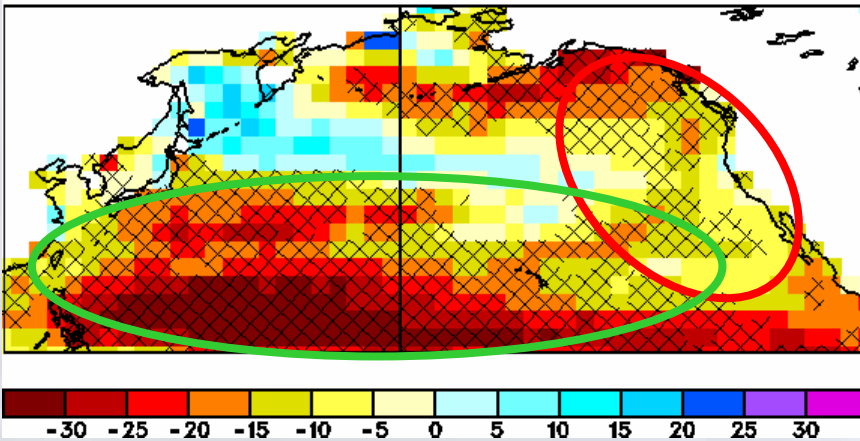


Attribution of 21st Century Changes

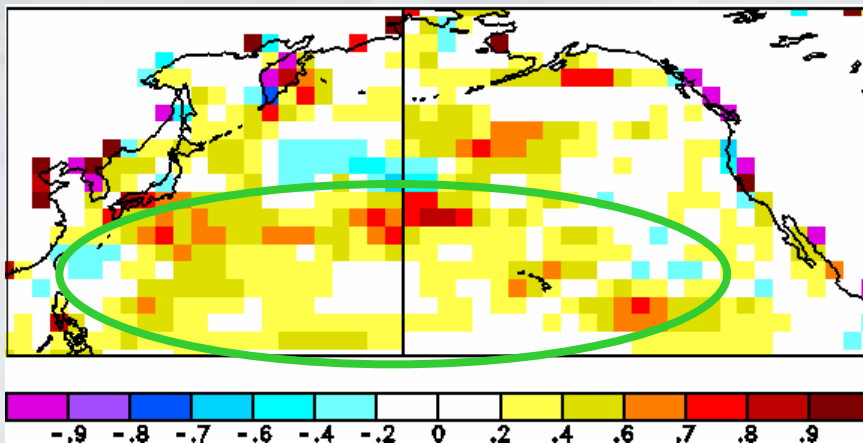
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ΔmaxMLD %

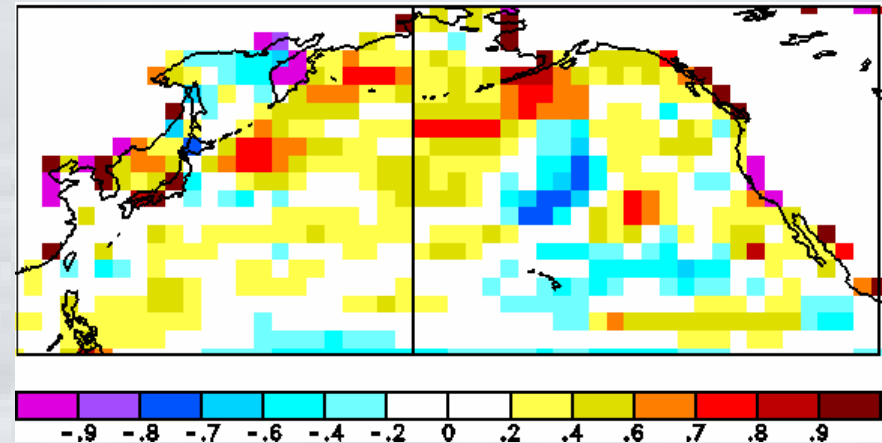
(2090-99) – (1990-99) $\text{corr}(\Delta\text{maxMLD}, \Delta\text{NSS})$



$\text{corr}(\Delta\text{maxMLD}, \Delta|\tau|)$



$\text{corr}(\Delta\text{maxMLD}, \Delta\text{cooling})$

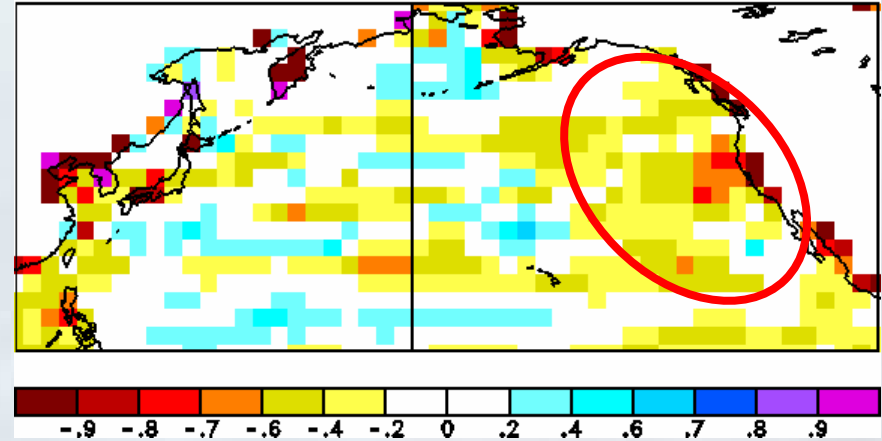
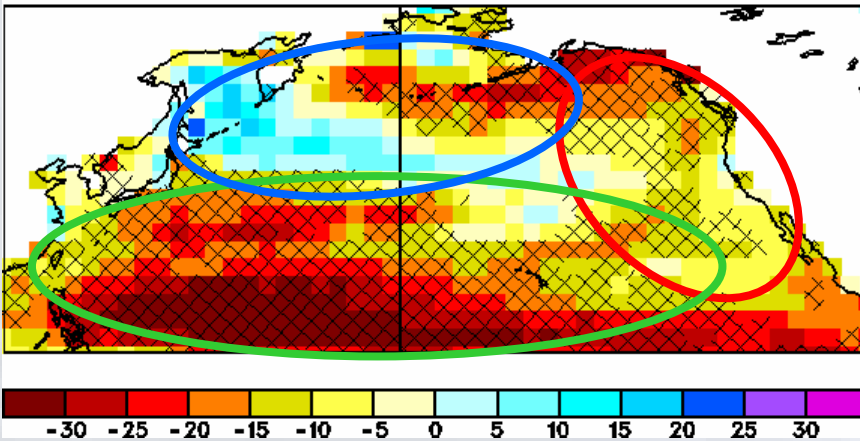


Attribution of 21st Century Changes

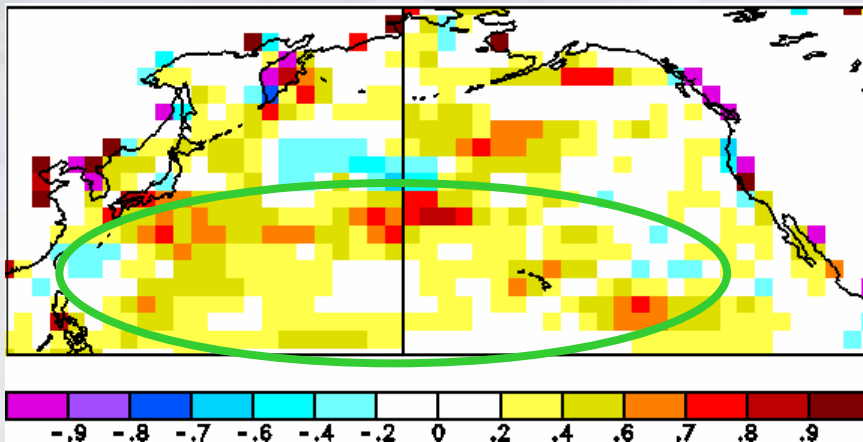
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ΔmaxMLD %

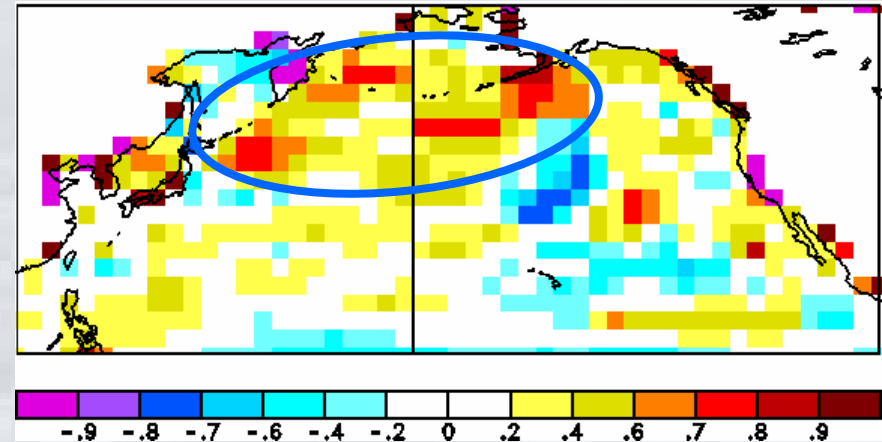
(2090-99) – (1990-99) $\text{corr}(\Delta\text{maxMLD}, \Delta\text{NSS})$



$\text{corr}(\Delta\text{maxMLD}, \Delta|\tau|)$



$\text{corr}(\Delta\text{maxMLD}, \Delta\text{cooling})$



Global Impact of Mixed-Layer Shallowing

- Consider changes in *mixed layer volume* = volume of ocean annually in contact with atmosphere, for different models, epochs

CENTRE	MODEL	1990s ML Vol 10⁷ km³	% change 1940s-90s	1990s– 2040s	2040s – 2090s	1990s– 2090s
BCCR	BCM2.0	4.4	-2.8	-4.3	-4.9	-9.2
Bonn/KMA	ECHO-G	3.0	-2.2	-10.7	-11.6	-22.3
CCCma	CGCM3.1/T63	2.5	-7.1	-5.9	-5.1	-11.0
CCSR	MIROC3.2med	3.7	-4.7	-13.5	-4.8	-18.3
CNRM	CM3	2.4	-10.4	-11.4	-9.4	-20.8
CSIRO	Mk3.0	5.5	-11.2	-9.7	-13.2	-22.9
GFDL	CM2.0	3.9	-1.3	-7.0	-7.2	-14.2
GFDL	CM2.1	4.9	-5.0	-19.3	-10.6	-29.9
GISS	AOM	7.9	-7.0	-13.1	-11.0	-24.1
GISS	EH	6.9	-4.8	-11.4	-11.7	-23.1
GISS	ER	8.6	-3.0	-14.6	-5.5	-20.1
INGV	ECHAM4/OPA	2.9	-6.8	-11.3	-4.8	-16.1
IPSL	CM4	2.4	-5.9	-5.2	-6.6	-11.8
MPI	ECHAM5/OM	2.3	-3.7	-6.9	-8.2	-15.1
MRI	CGCM2.3.2	2.3	-3.0	-6.4	-5.0	-11.4
NCAR	CCSM3.0	3.2	-3.0	-8.8	-4.5	-13.3.
UKMO	HadCM3	3.5	-1.8	-5.1	-4.5	-9.6
Multi-Model	Average	4.1	-5.2	-9.7	-8.5	-18.2

Conclusions

- ML in models *universally* shallows under anthropogenic warming
- Significant shallowing has already occurred
- Observed trend at Station P far exceeds that in most models
- Primary influence on MLD appears to differ with region:
 - increased near-surface stratification in NE Pacific
 - decreased winter cooling in N central, NW Pacific
 - decreased wind speed in tropics/subtropics
- Maximum annual ML volume decreases by 10-30% in 21st century → reduced ocean uptake of heat, CO₂
→ *positive feedback?*
(though other influences such as area of Southern Ocean isopycnal outcrops may trend oppositely: Russell et al. *J Clim* 2006)