Role of Tibetan Plateau in the formation of the Global Meridional Overturning Circulation

YANG Haijun[1,2], WEN Qin[2] and YAO Jie[2]
[1]Department of Atmospheric and Oceanic Sciences, Fudan University
[2]LaCOAS and Department of Atmospheric and Oceanic Sciences
School of Physics, Peking University
Email: yanghj@fudan.edu.cn

Tibetan Plateau (TP): the 3rd Pole

Total Area: 2.5 million km^2, Elevation: 4000 m

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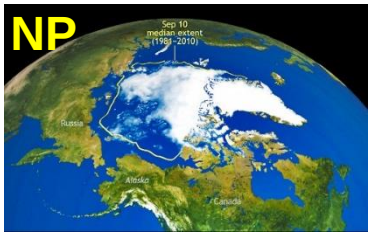
A Fundamental Question: *With* / *Without* TP



- Greenland Ice Melting ➔ **+7m** ⇑ global ocean
- Antarctic Ice: 70% FW，90% Ice Melting ➔ **+61m** ⇑ global ocean
- ***With / Without*** TP: Sea level and fundamental climate differences?
  25 billion m^3 freshwater around TP

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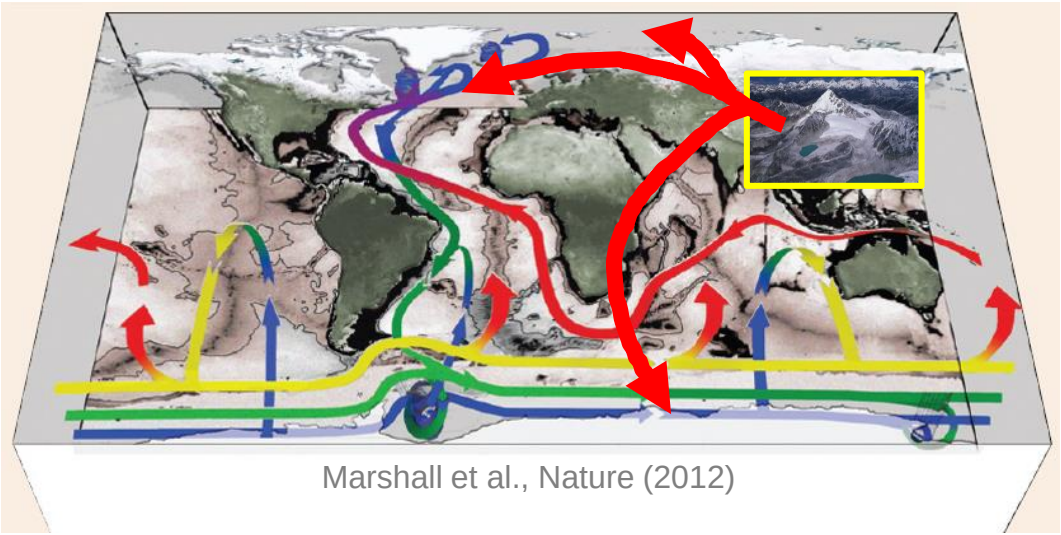
TP: A *Global* Perspective

How and to what extent?



Marshall et al., Nature (2012)

TP → NH vs. SH Asymmetry → Energy & Hydrological Cycle → Wind & Freshwater → Global Conveyor Belt

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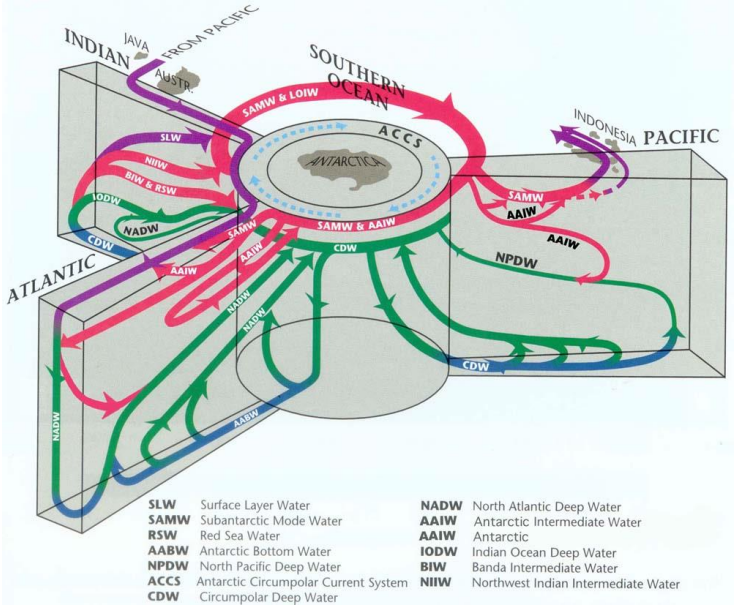
Global Meridional Overturning Circulation

Energy and Freshwater Balance

Weak

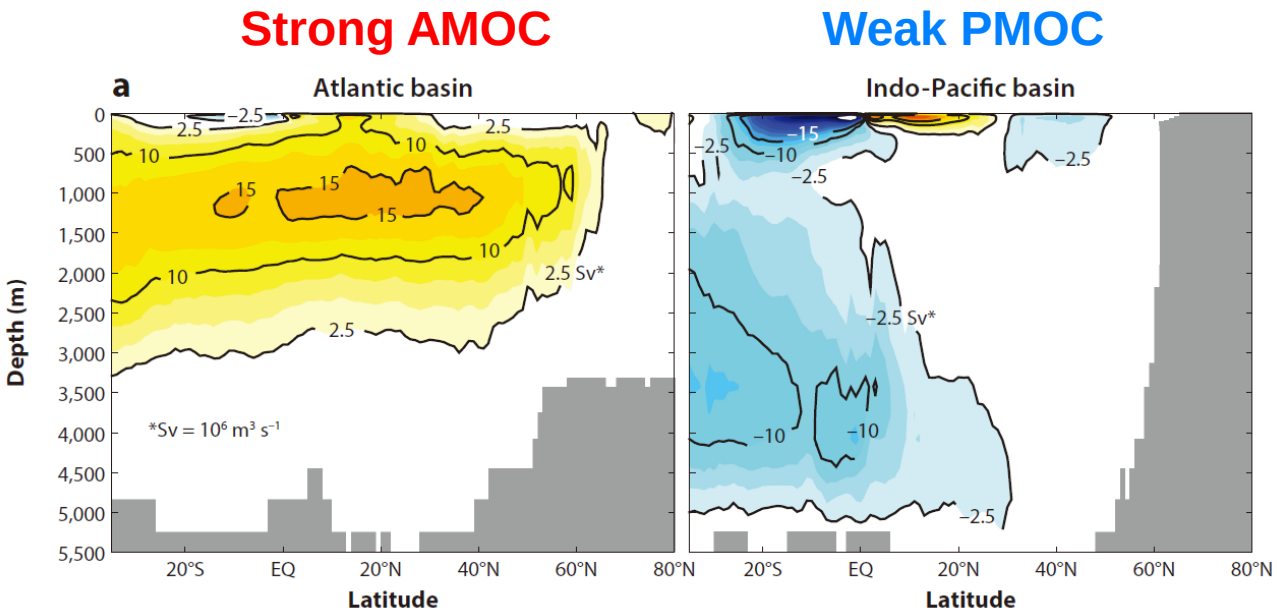
AMOC



PMOC

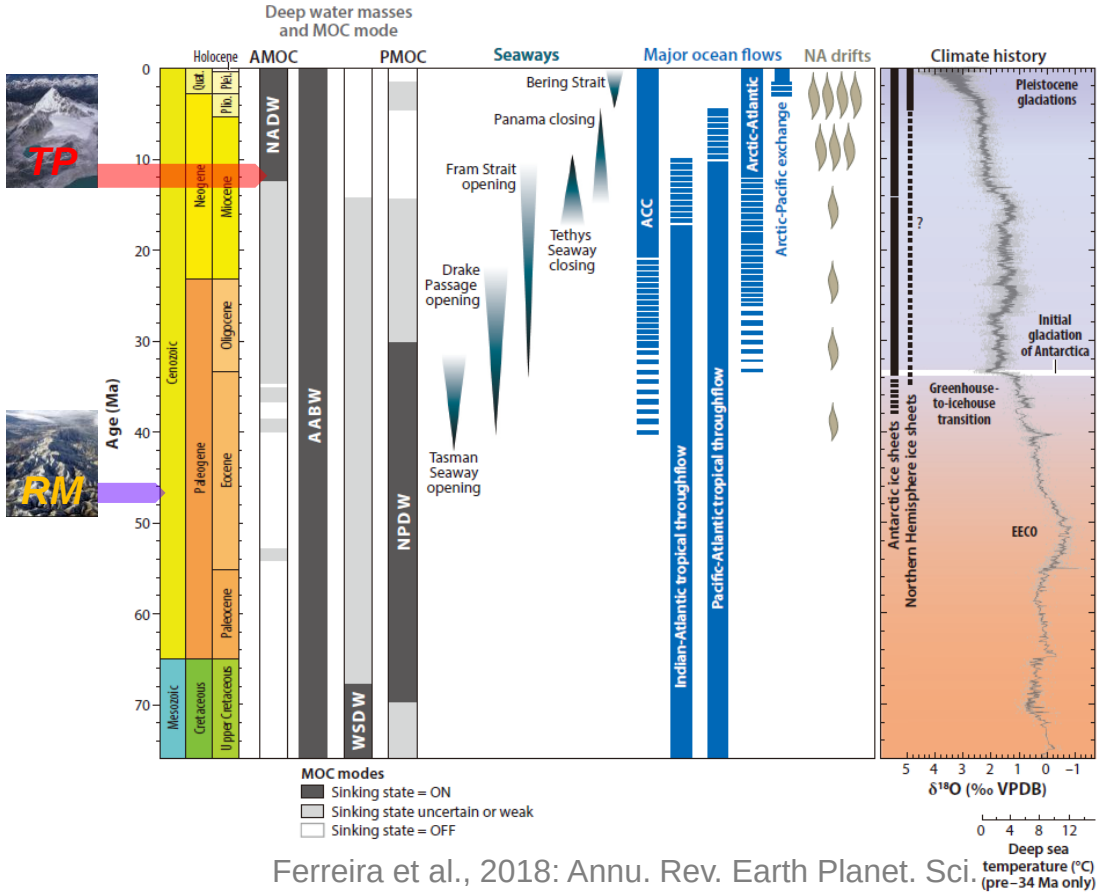
Schmitz (1997) Overturning circulation: Southern Ocean View

GMOC Now



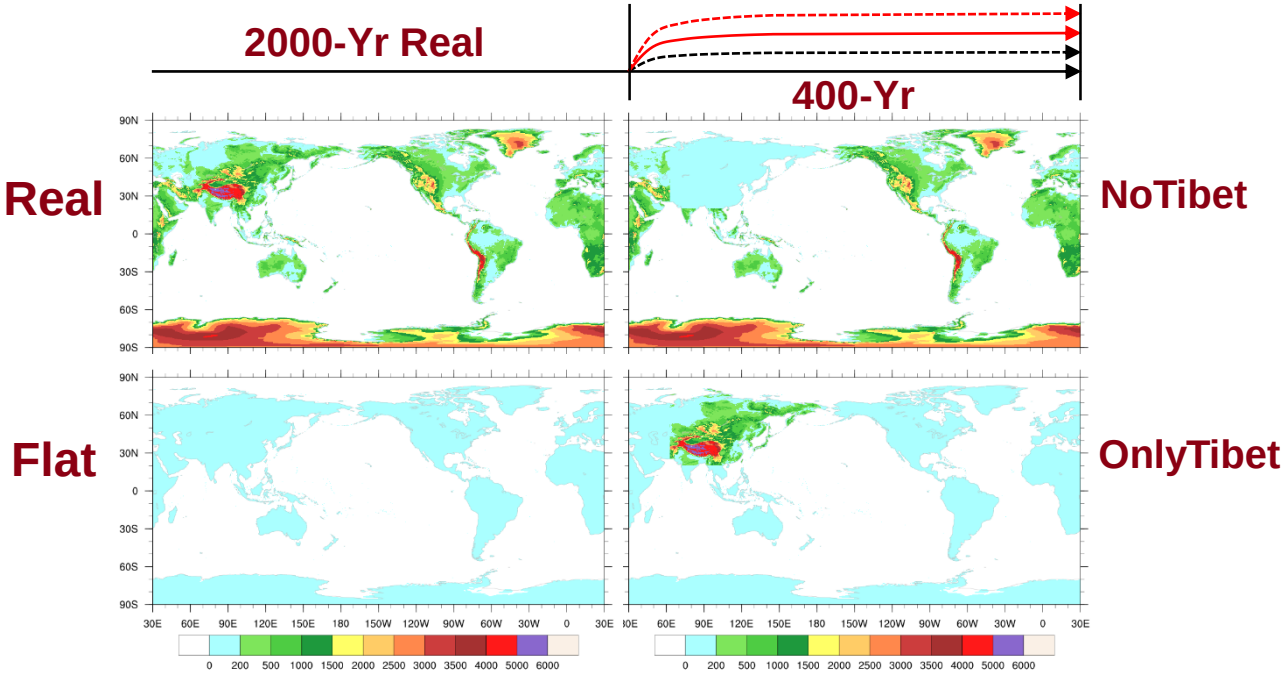
Ferreira et al., 2018: Annu. Rev. Earth Planet. Sci.

Geological History of *GMOC*



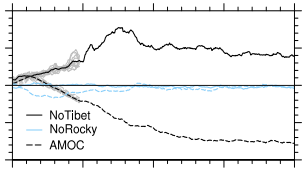
Ferreira et al., 2018: Annu. Rev. Earth Planet. Sci.

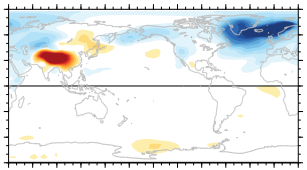
Coupled Earth System Model

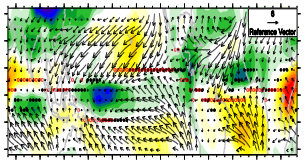


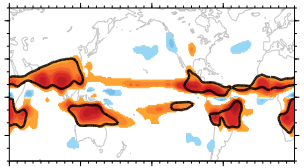
NCAR CESM1.0: CAM5 / POP2 / CLM4 / CICE4 / Glimmer-CISM

TP in Climate System









- **Yang et al., TP role in global climate: annual mean (*Published*)**
- **Yang et al., TP in shaping AMOC (*Published*)**
- **Wen et al., TP in see-saw of PMOC and AMOC (*Published*)**
- **Wen et al., TP effect on ENSO variability (*Published*)**
- Wen et al., TP effect on the AABW (*Submitted*)
- Chen et al., TP effect on the North African precipitation (*Submitted*)
- Jiang et al., Rocky Mountain effect on GMOC (*Submitted*)
- Yao et al., TP role in global climate: SC and monsoon (*Submitted*)
- Shen et al., TP effect on Atlantic ITCZ (*Submitted*)

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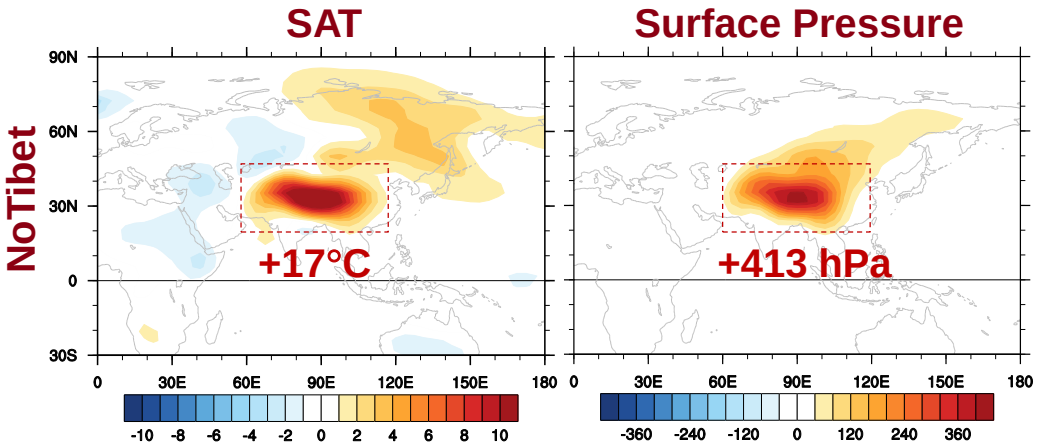
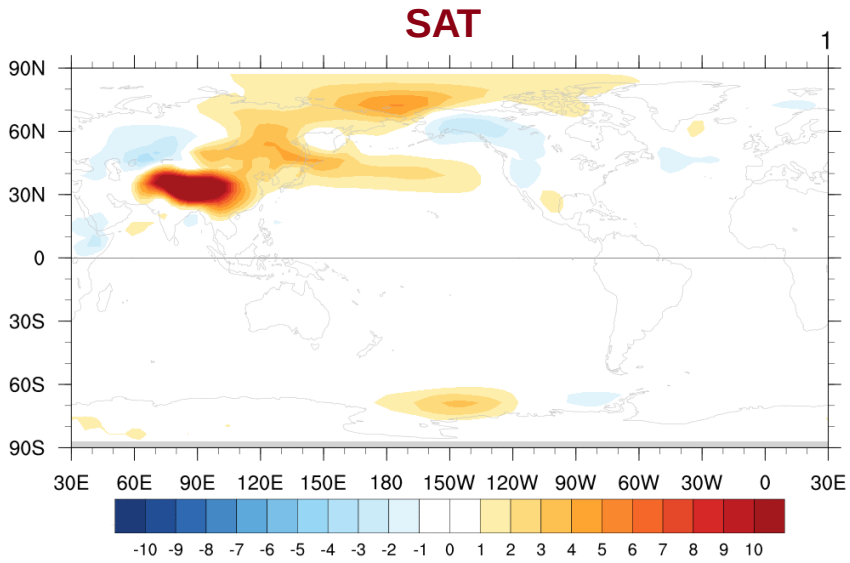
TP Forcing: *Thermal* and *Dynamical*



Lapse Rate T **~ 4 km x 7 ~ 28°C**

SAT Evolution w/o TP



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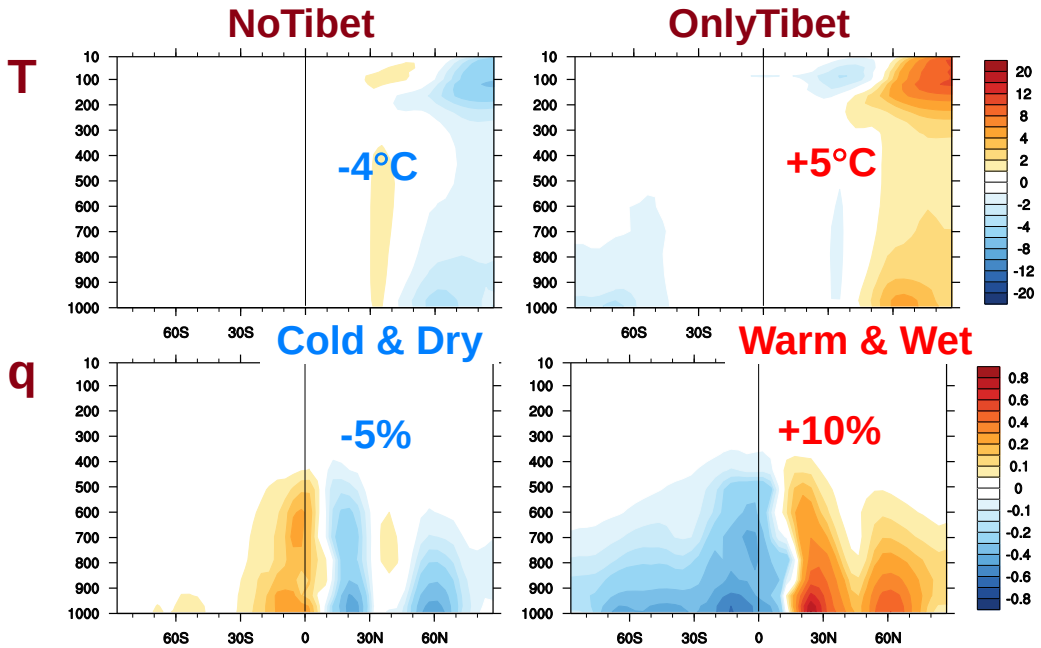
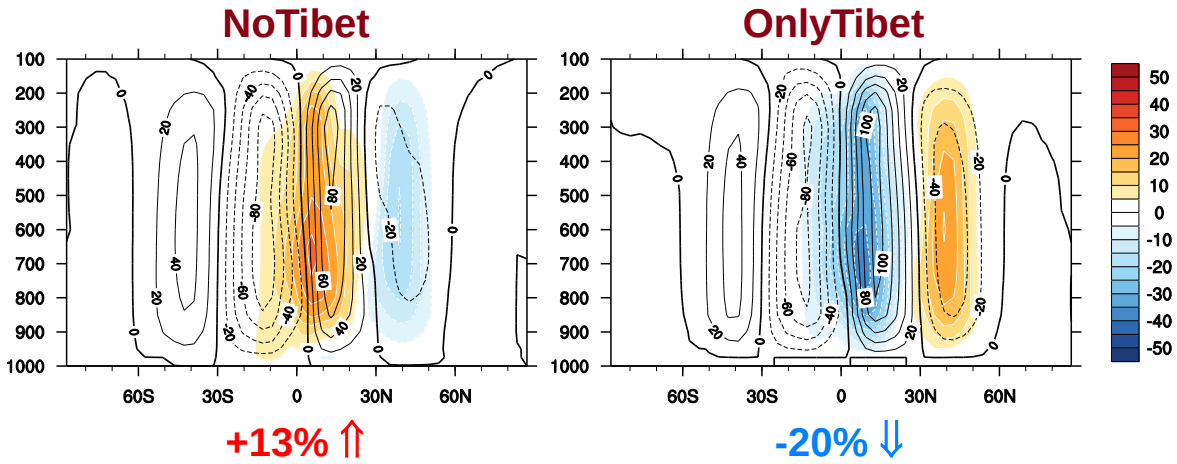
Atmosphere T and Moisture



Hadley Cell


NoTibet
OnlyTibet
100
200
300
400
500
600
700
800
900
1000
60S
30S
0
30N
60N
50
40
30
20
10
0
-10
-20
-30
-40
-50
+13% ⇑
-20% ⇓

Preliminary Results

		NoTibet	OnlyTibet
Atmos	TOA (PW)	+0.2	-0.04
	Air T (°C)	-4.0	+6.0
	SAT (°C)	-18.0	+19.0
	Air q (%)	-5.0	+10.0
	HC (%)	+13	-20
Ocean	SST (°C)	-8.0	+10.0
	SSS (psu)	-4.0	+6.0
	SSD (kg/m^3)	-3.0	+4.0

0 → 1 : Critical in Shaping Global Climate!

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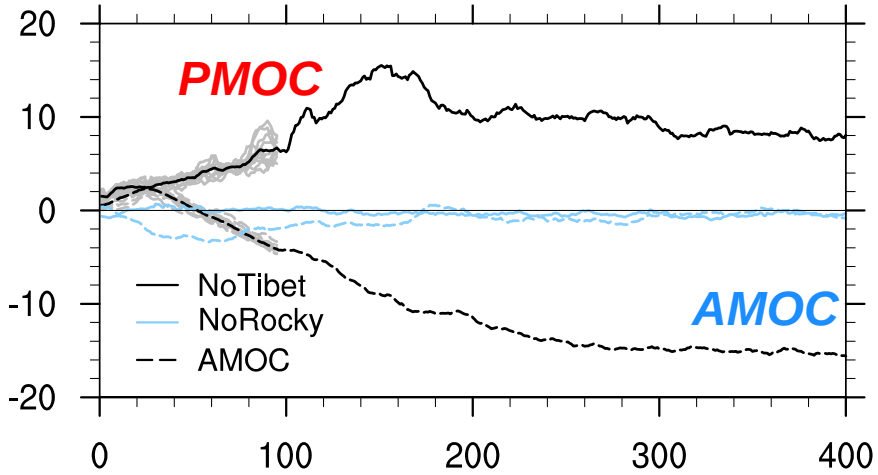
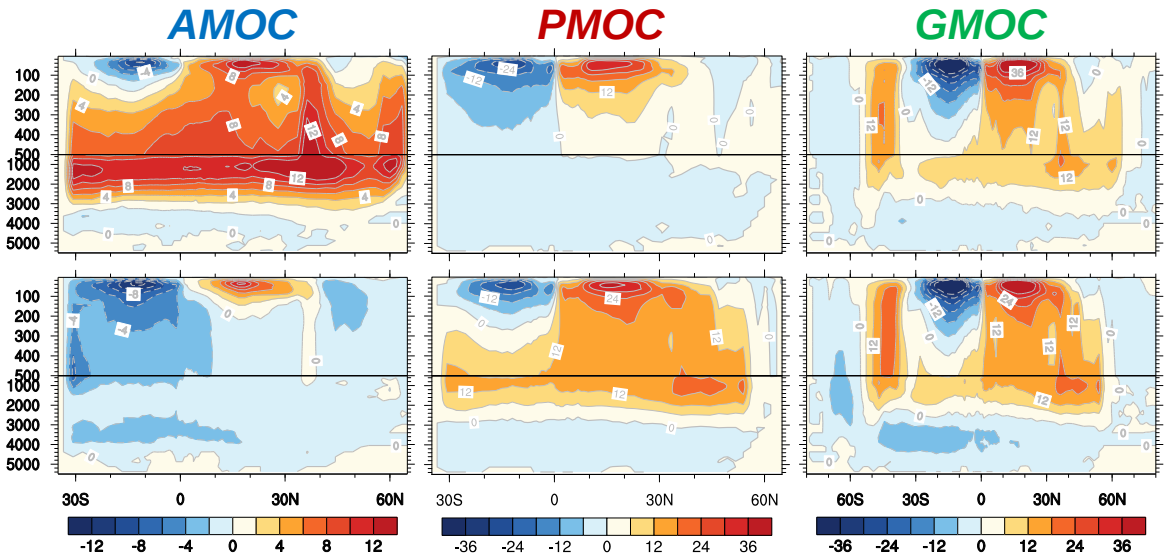
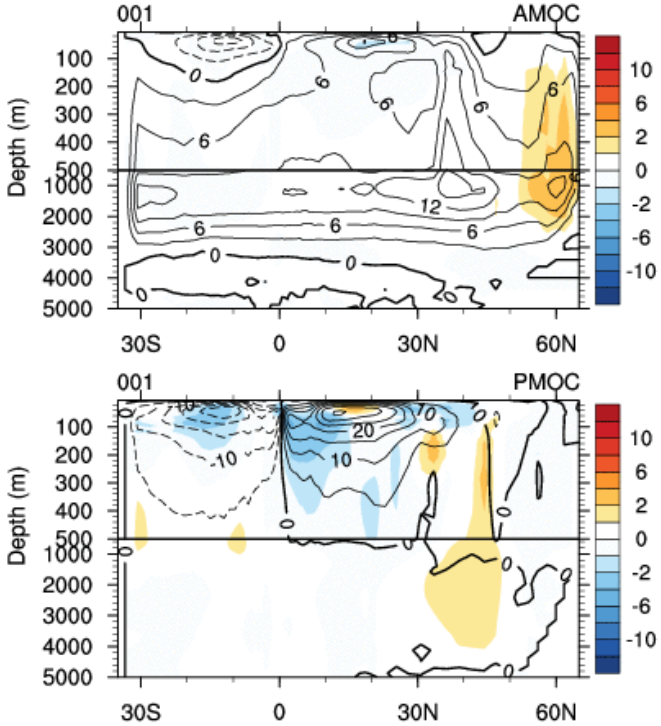
GMOC Index



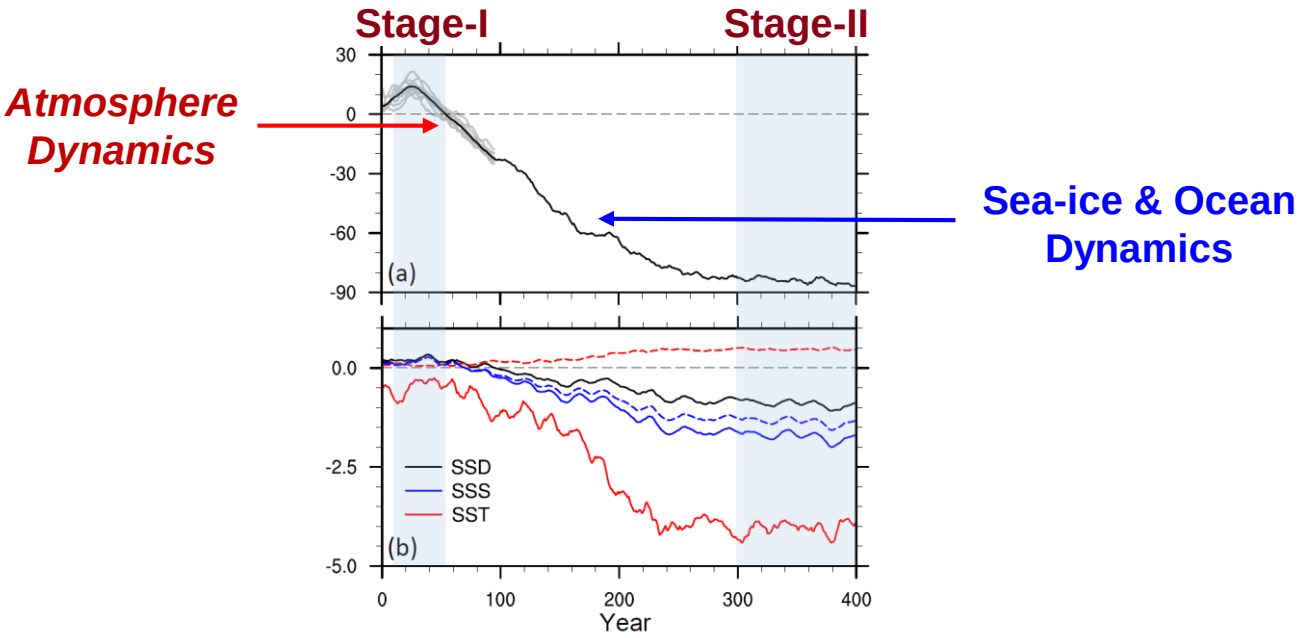
Global MOC


AMOC
PMOC
GMOC
Real
NoTibet
100
200
300
400
500
1000
2000
3000
4000
5000
30S
0
30N
60N
60S
-12 -8 -4 0 4 8 12
-36 -24 -12 0 12 24 36

AMOC vs. *PMOC*: See-Saw?

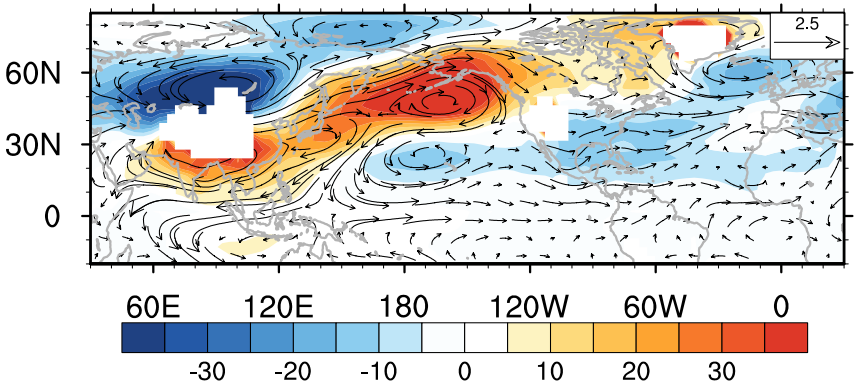


AMOC Evolution w/o TP

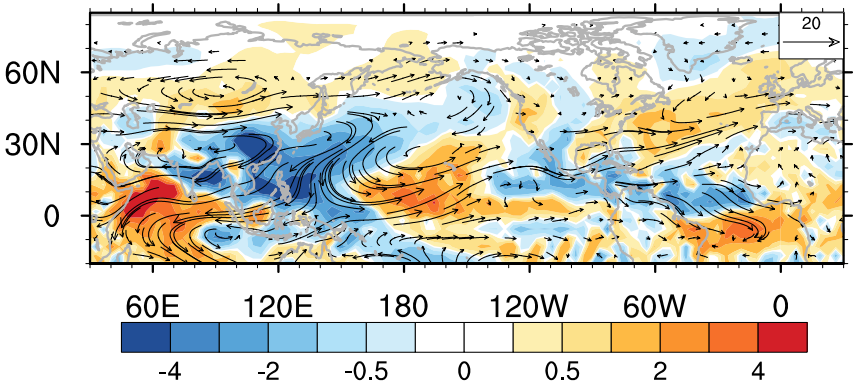


Teleconnection: From *TP* to *Atlantic*

850 hPa GH and Wind



Moisture Transport



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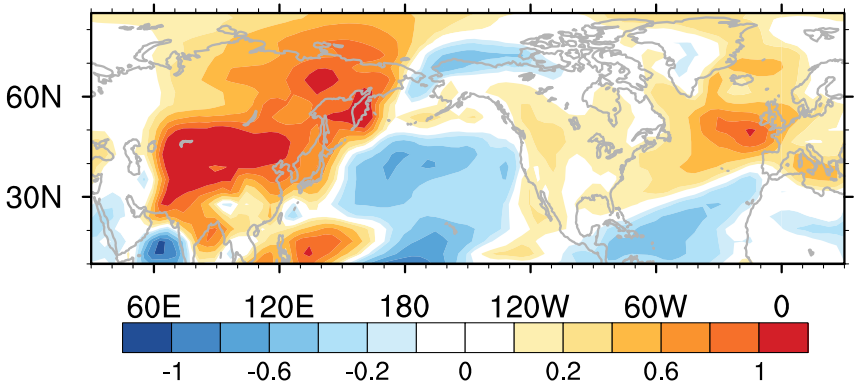
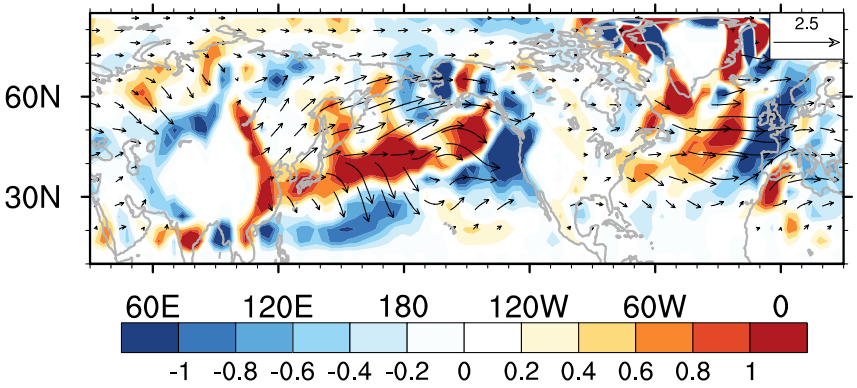
Teleconnection: From *TP* to *Atlantic*

10-m Wind Speed



850 hPa Wave Activity



Alan Plumb, JAS, 1985; Takaya & Nakamura, JAS, 1998

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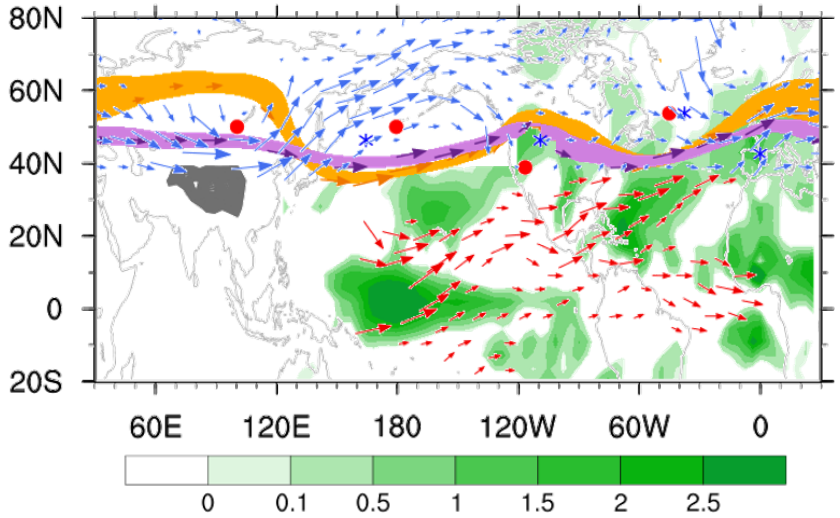
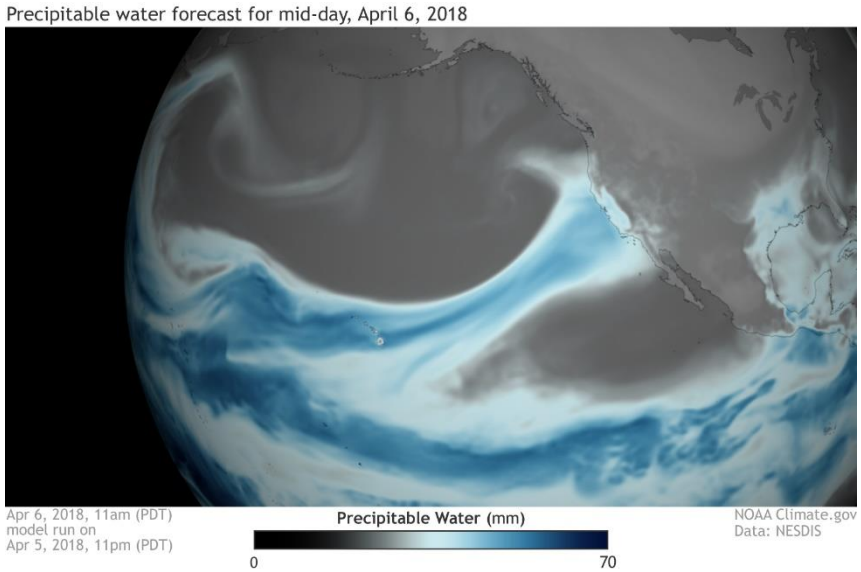
From *TP* to *AMOC: Atmosphere Dynamics*

Stationary Waves with Tibetan Plateau

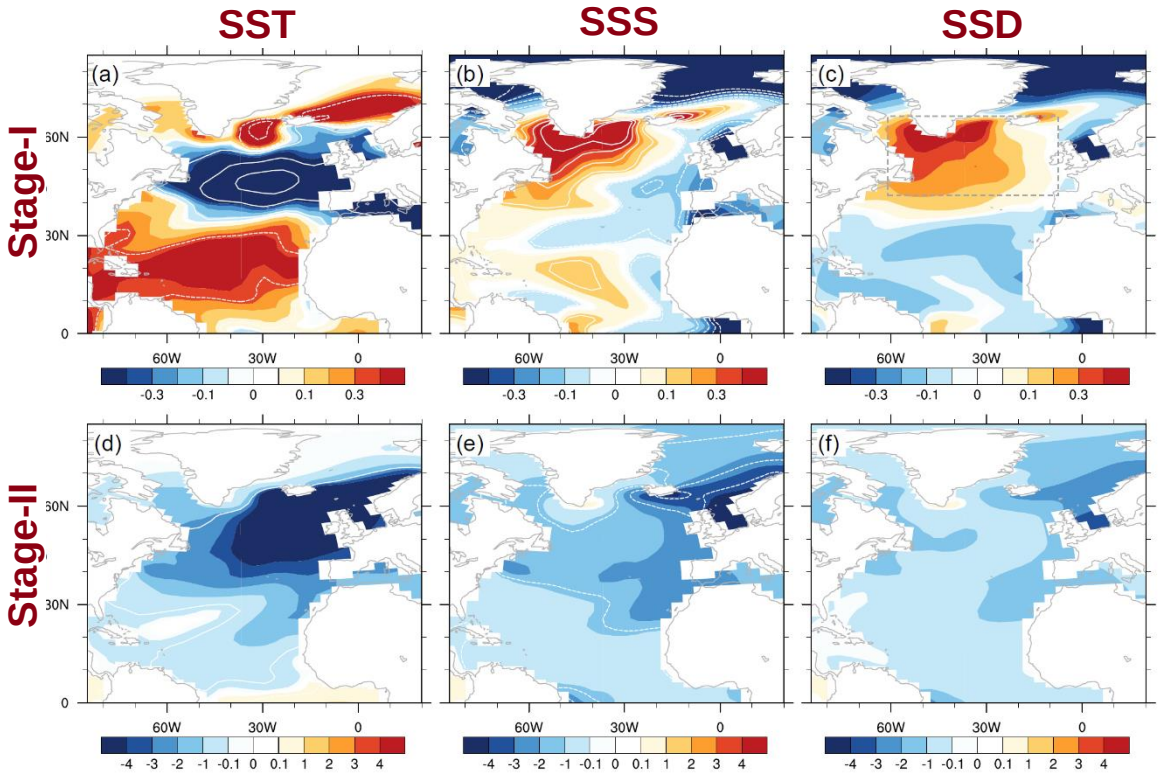


NoTibet → Annular mode ⇑ → Westerlies ⇑ → Moisture transport ⇑

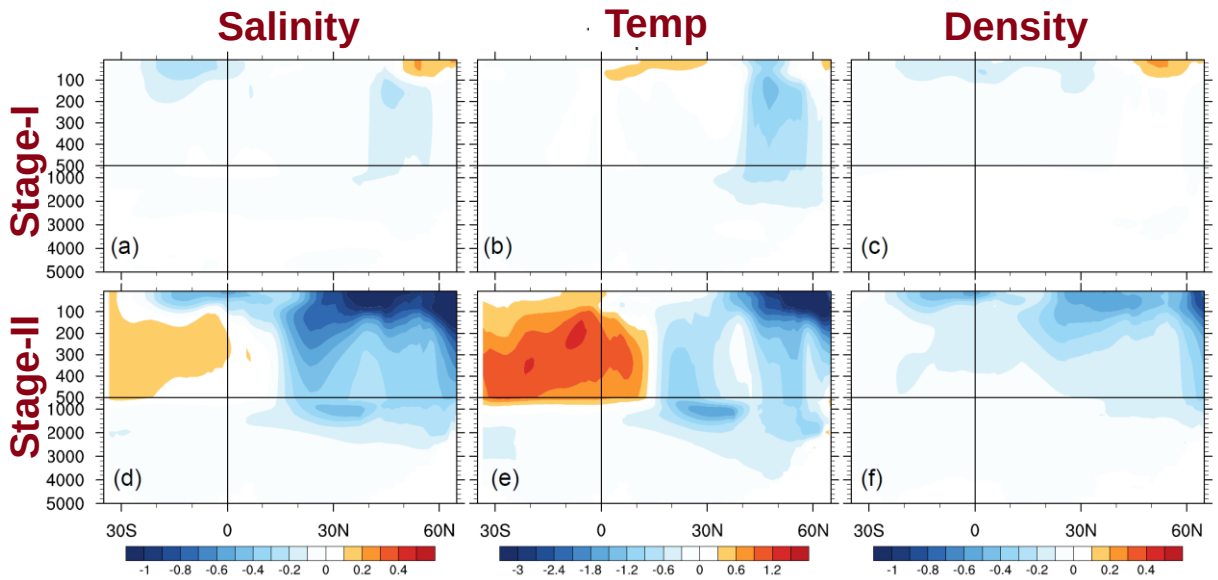
Atmosphere River



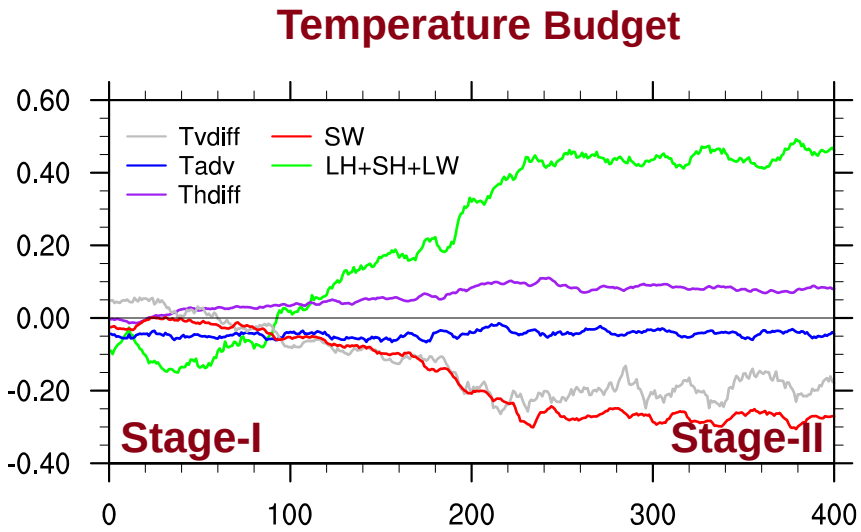
Ocean Change



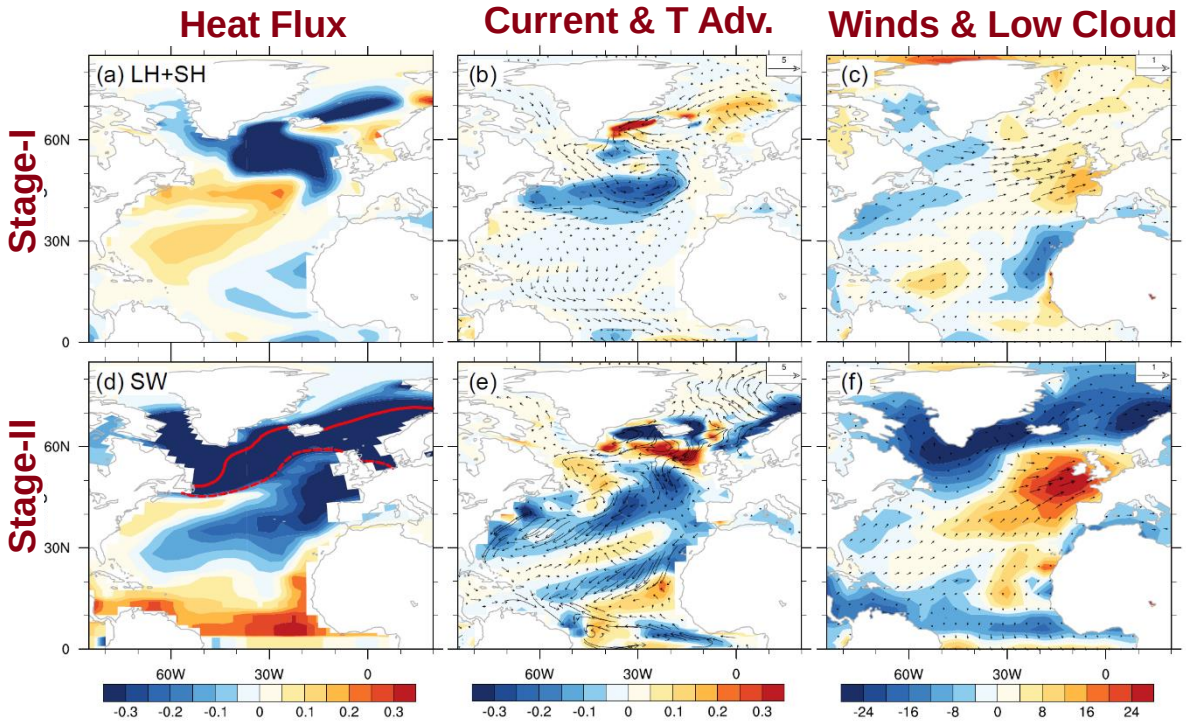
Ocean Change



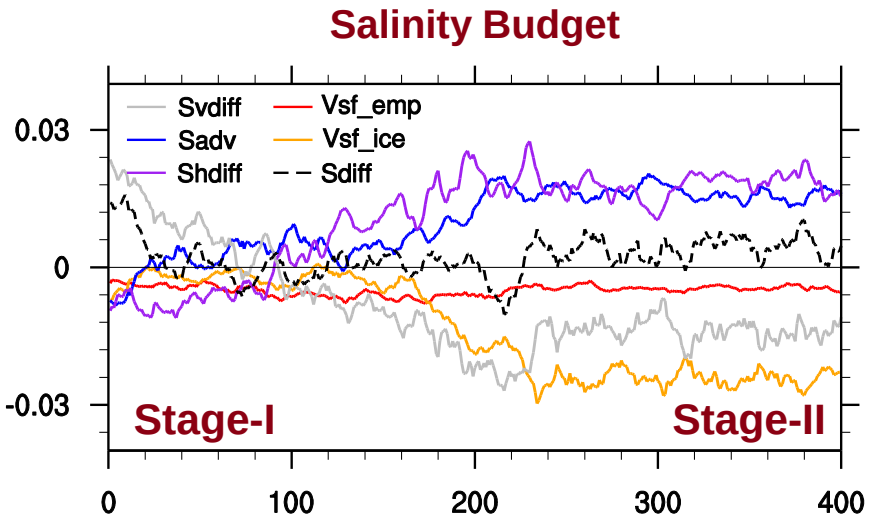
Mechanism for *Temp* Change



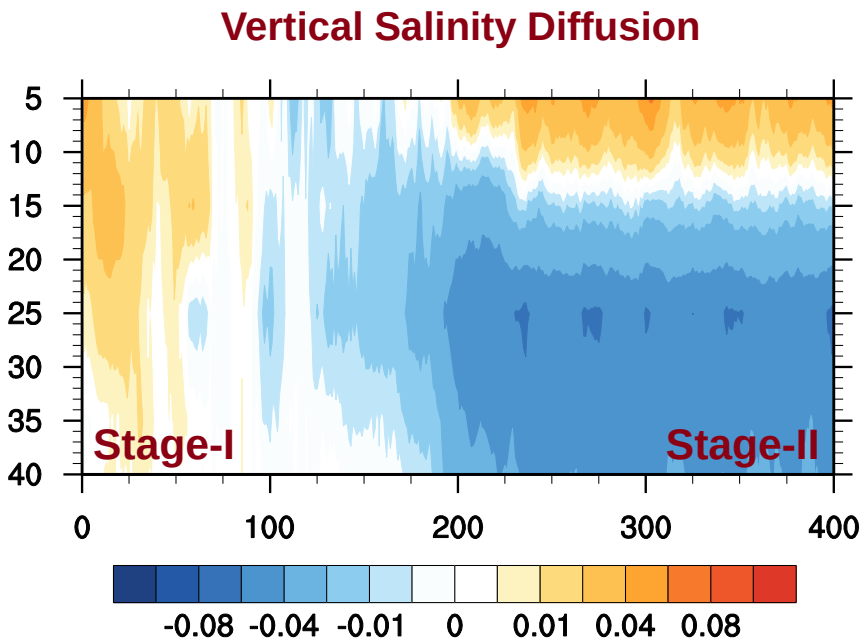
Mechanism for *Temp* Change



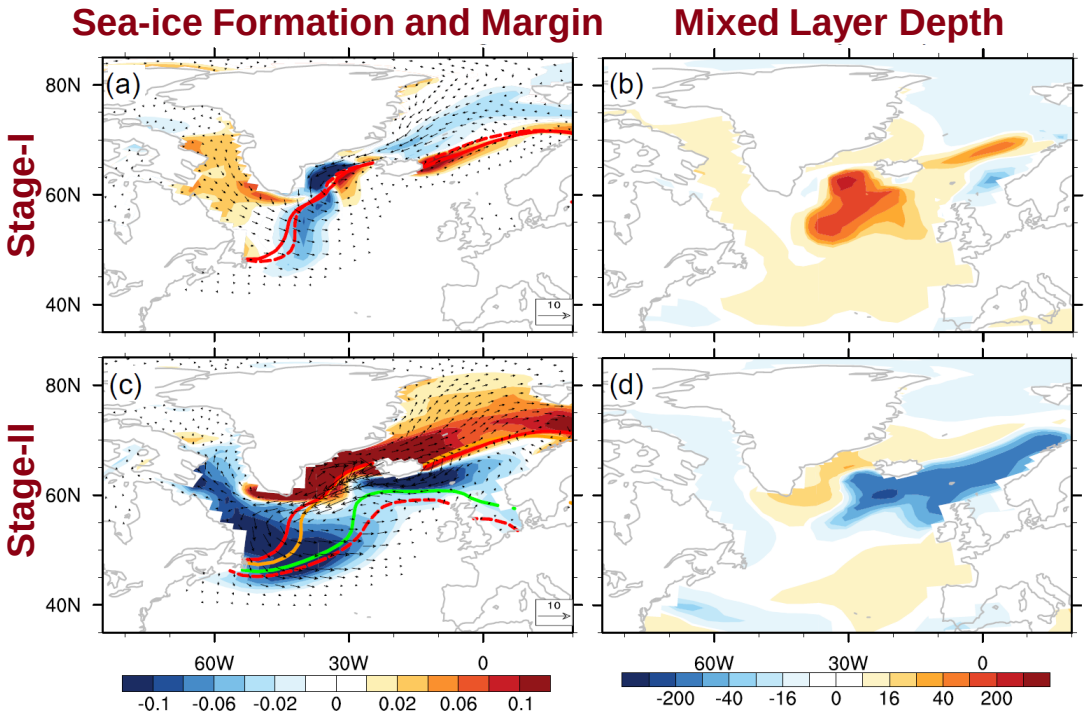
Mechanism for *Salinity* Change



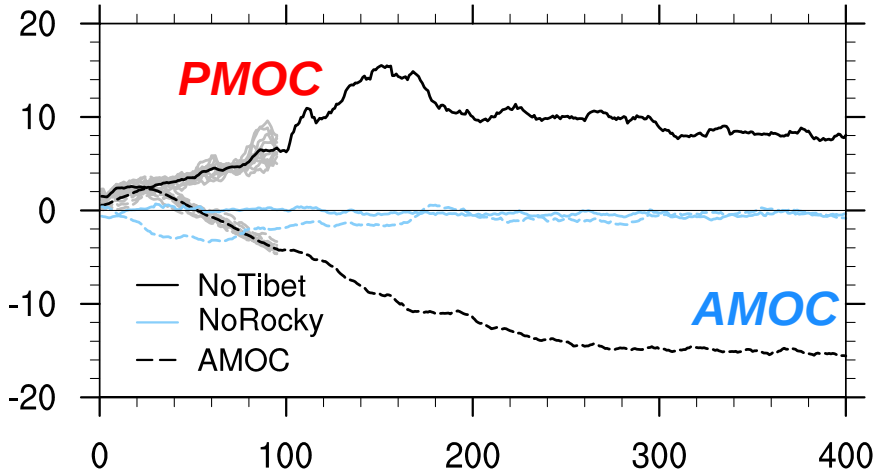
Mechanism for *Salinity* Change



Mechanism for *Salinity* Change

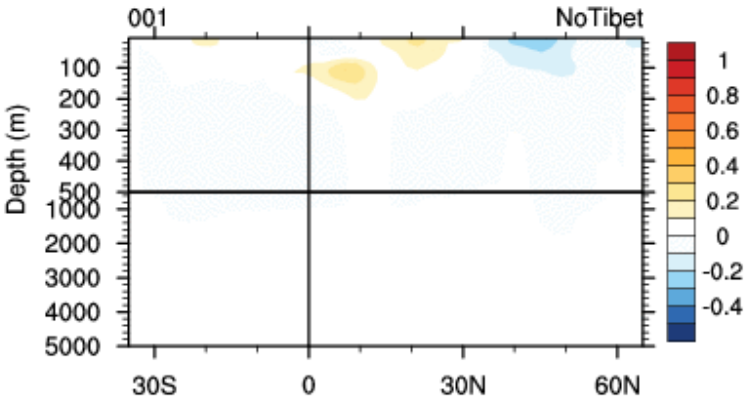


AMOC vs. PMOC

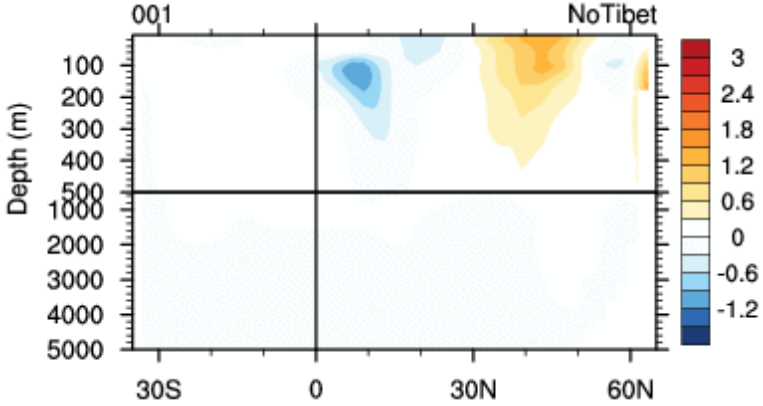


PMOC: Mechanism?

Density



Temperature



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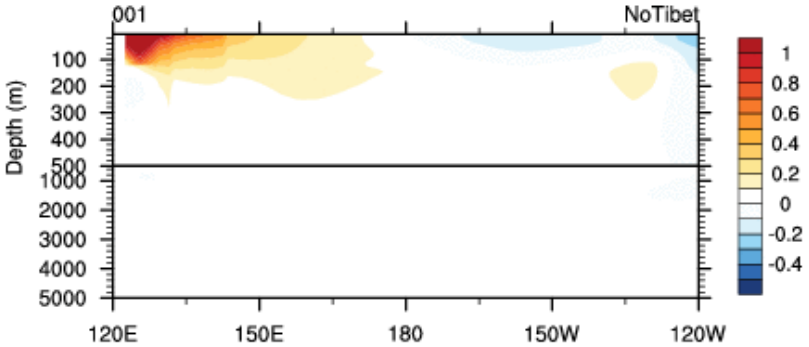
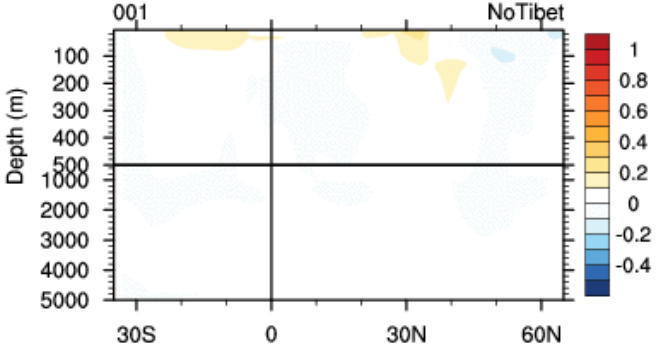
PMOC: *Salinity* Mechanism

Eastward



Southward & Downward



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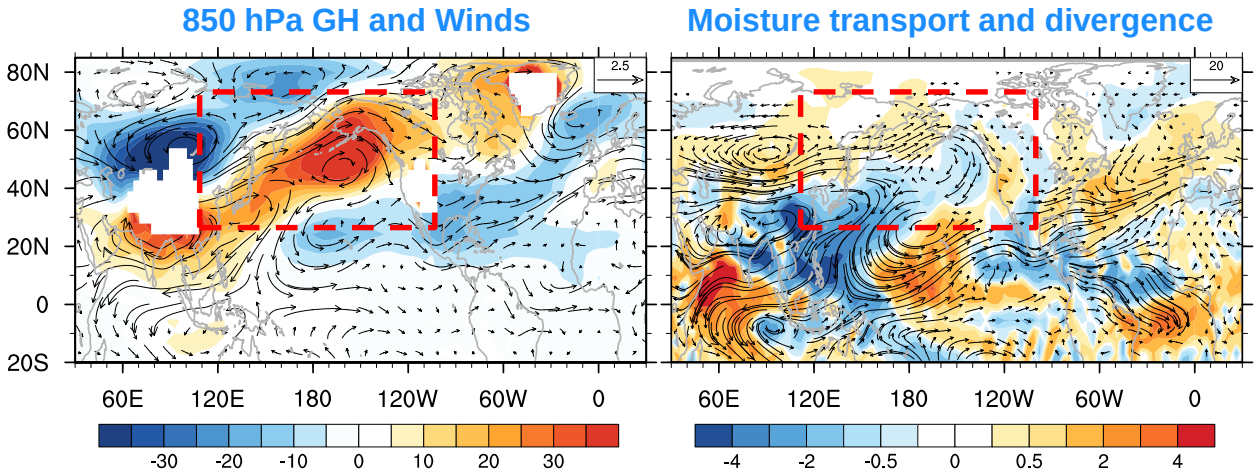
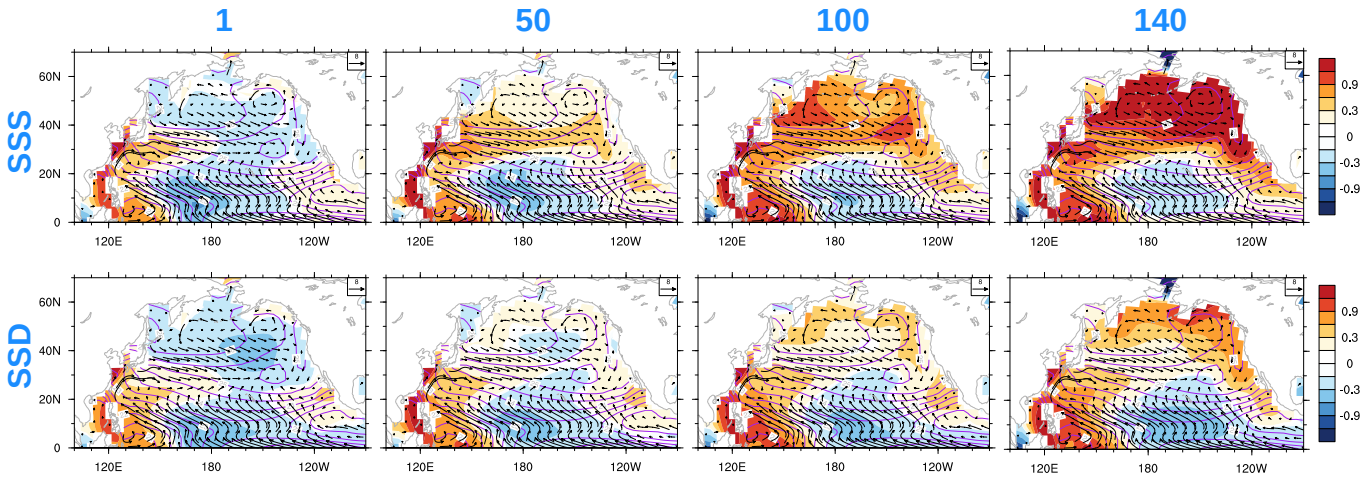
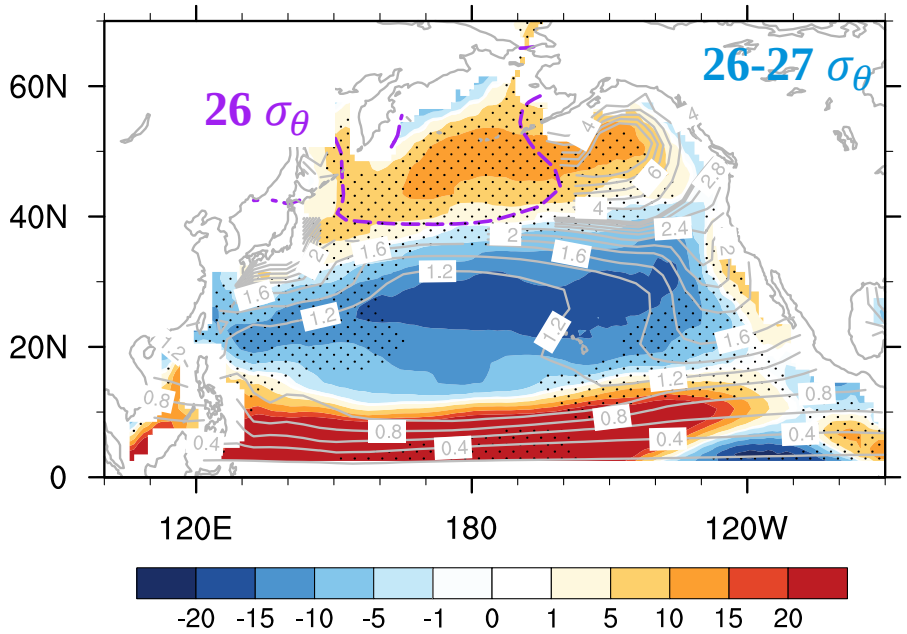
Atmospheric Changes



Surface Salinity and Density Changes

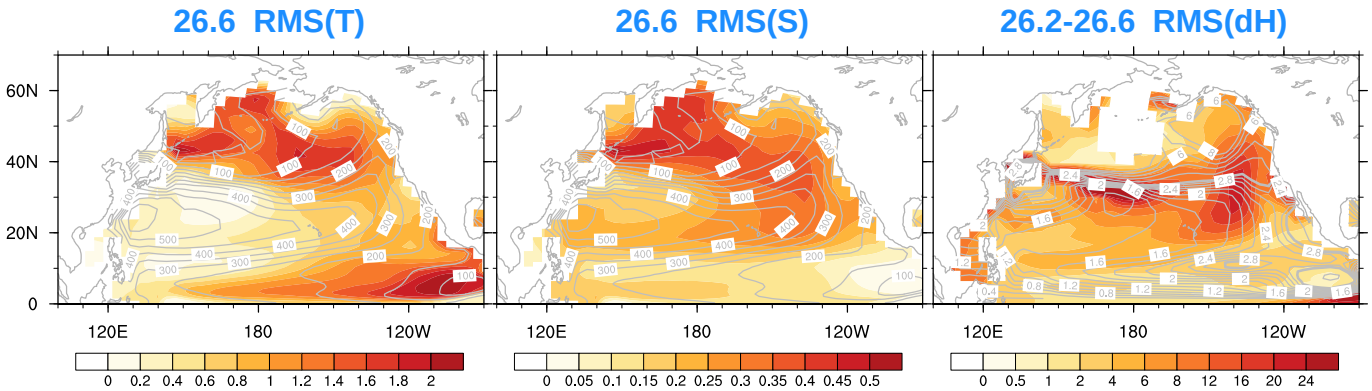


Ekman Pumping and PV



Black Dots: Enhanced Ekman Downwelling

RMS of *Temp*, *Salinity* and *Thickness*



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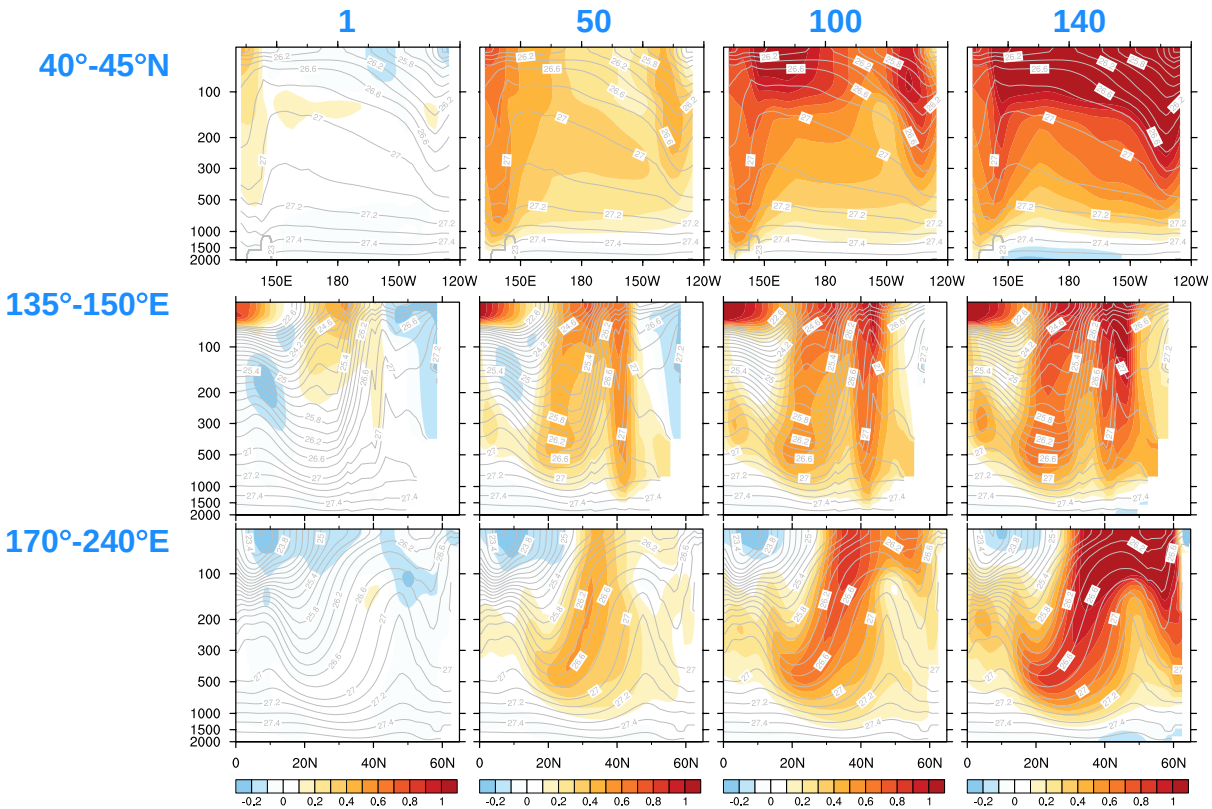
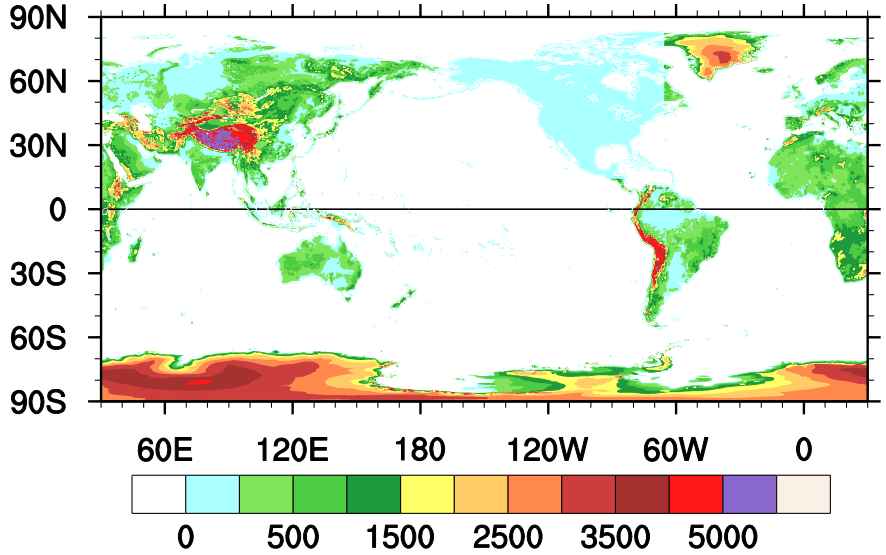
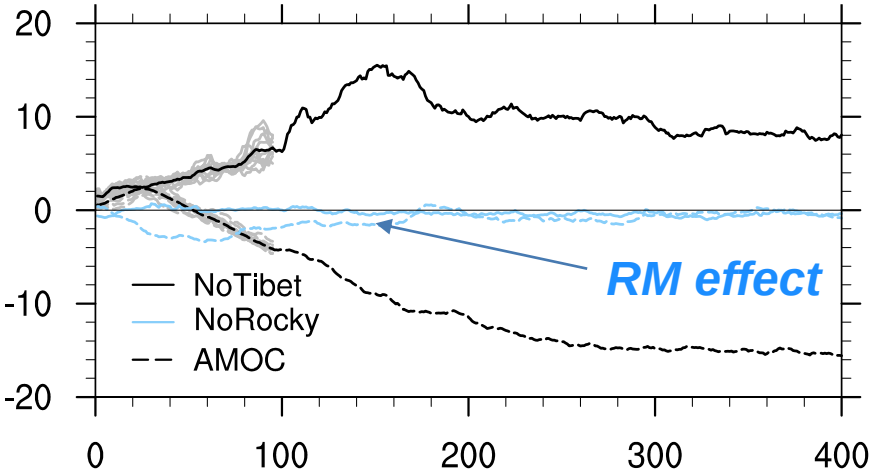
Salinity Subduction



Role of *Rocky* Mountain?

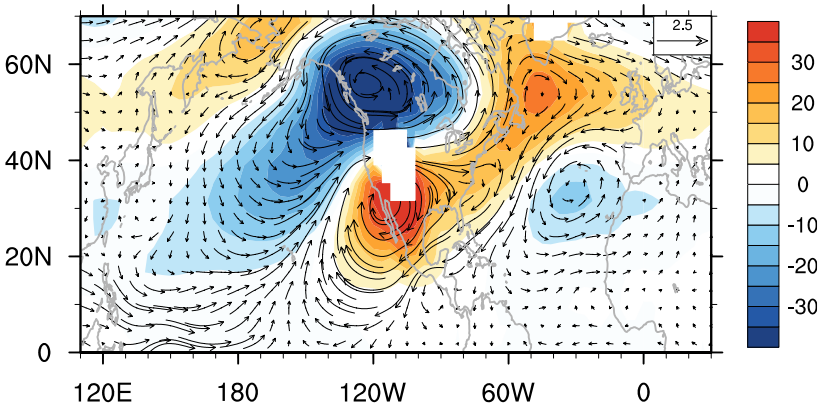


Rocky Mountain: No Role?

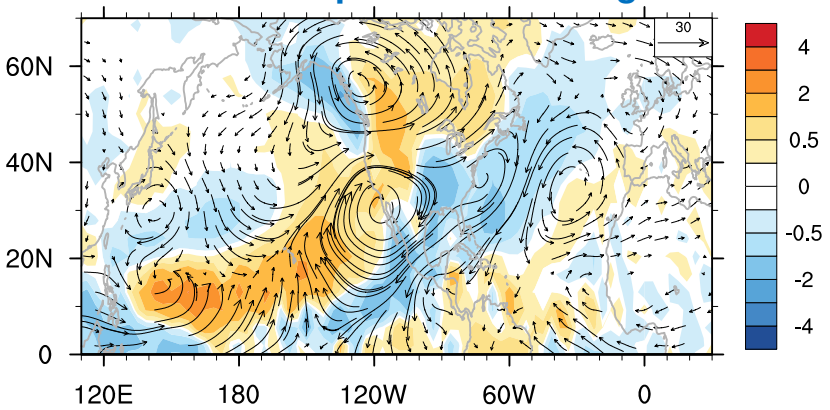


Rocky Mountain: Atmosphere Changes

850 hPa GPH and wind



Moisture transport and convergence



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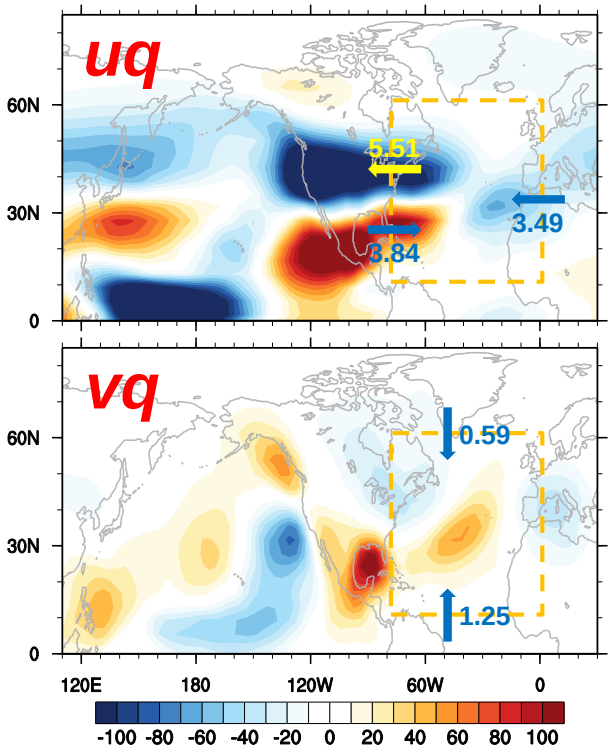
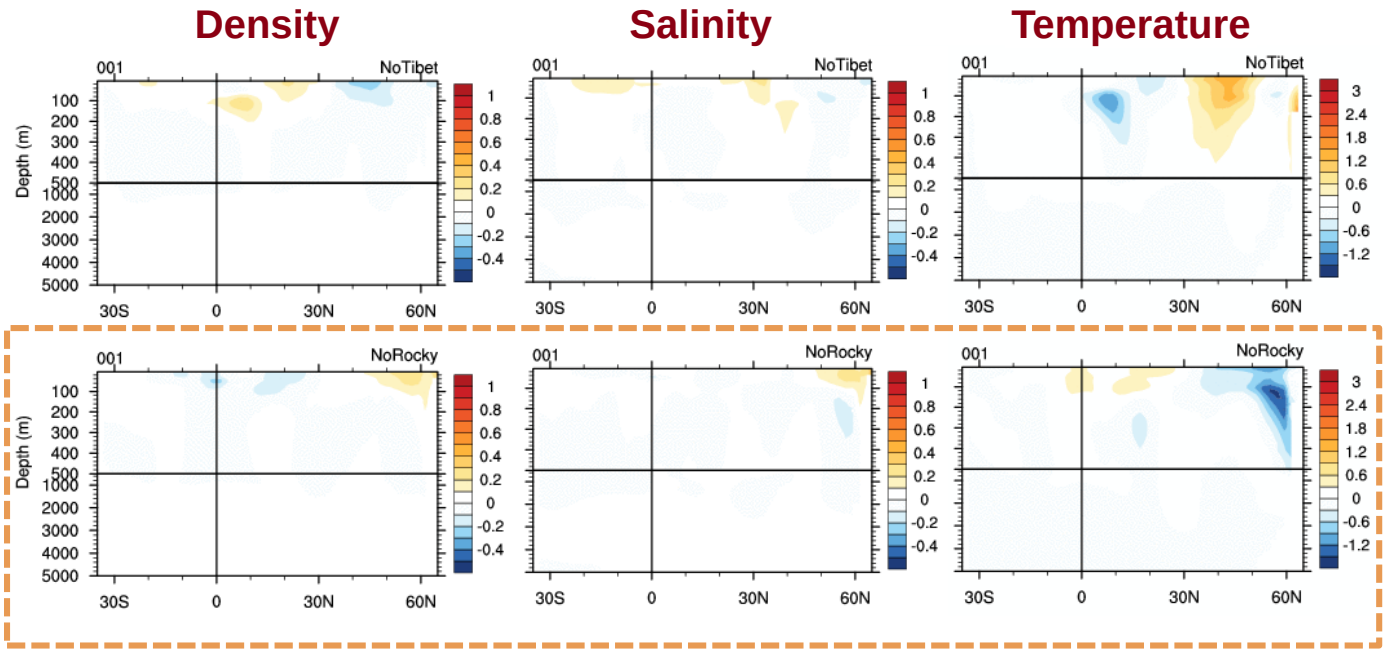
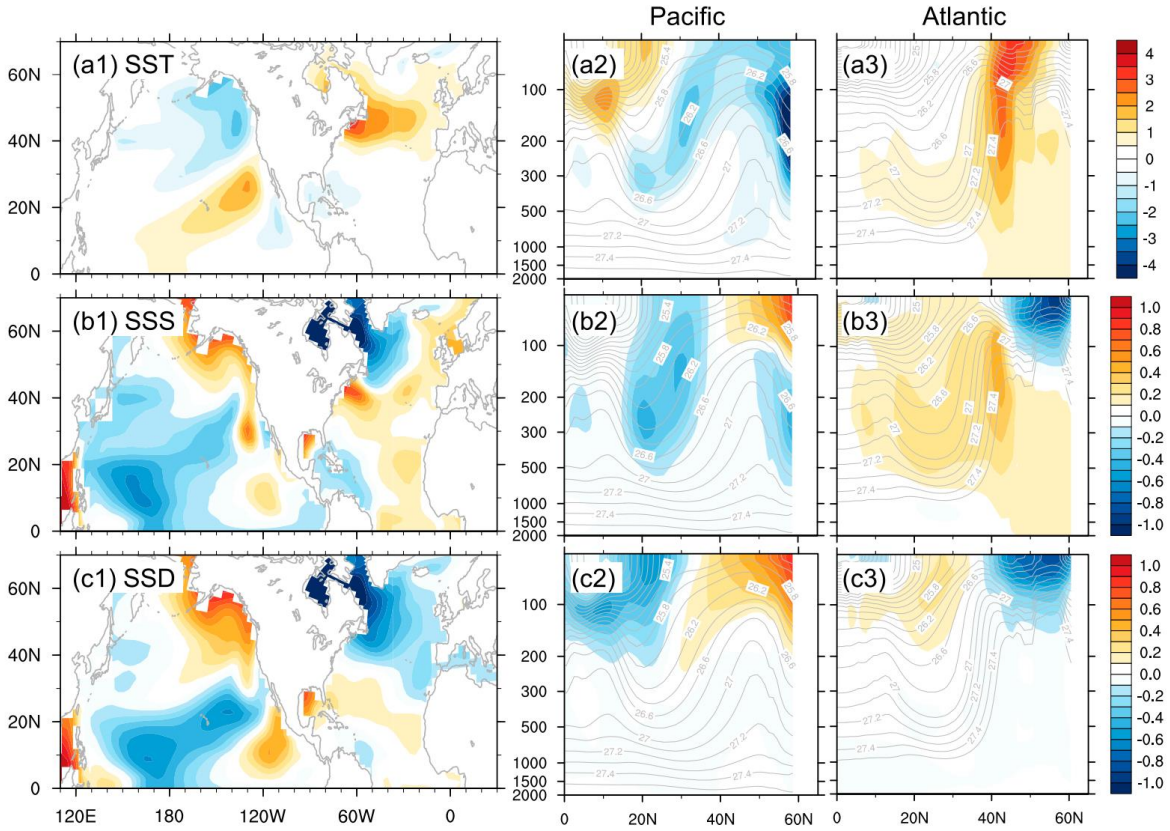
Rocky Mountain: Moisture Transport



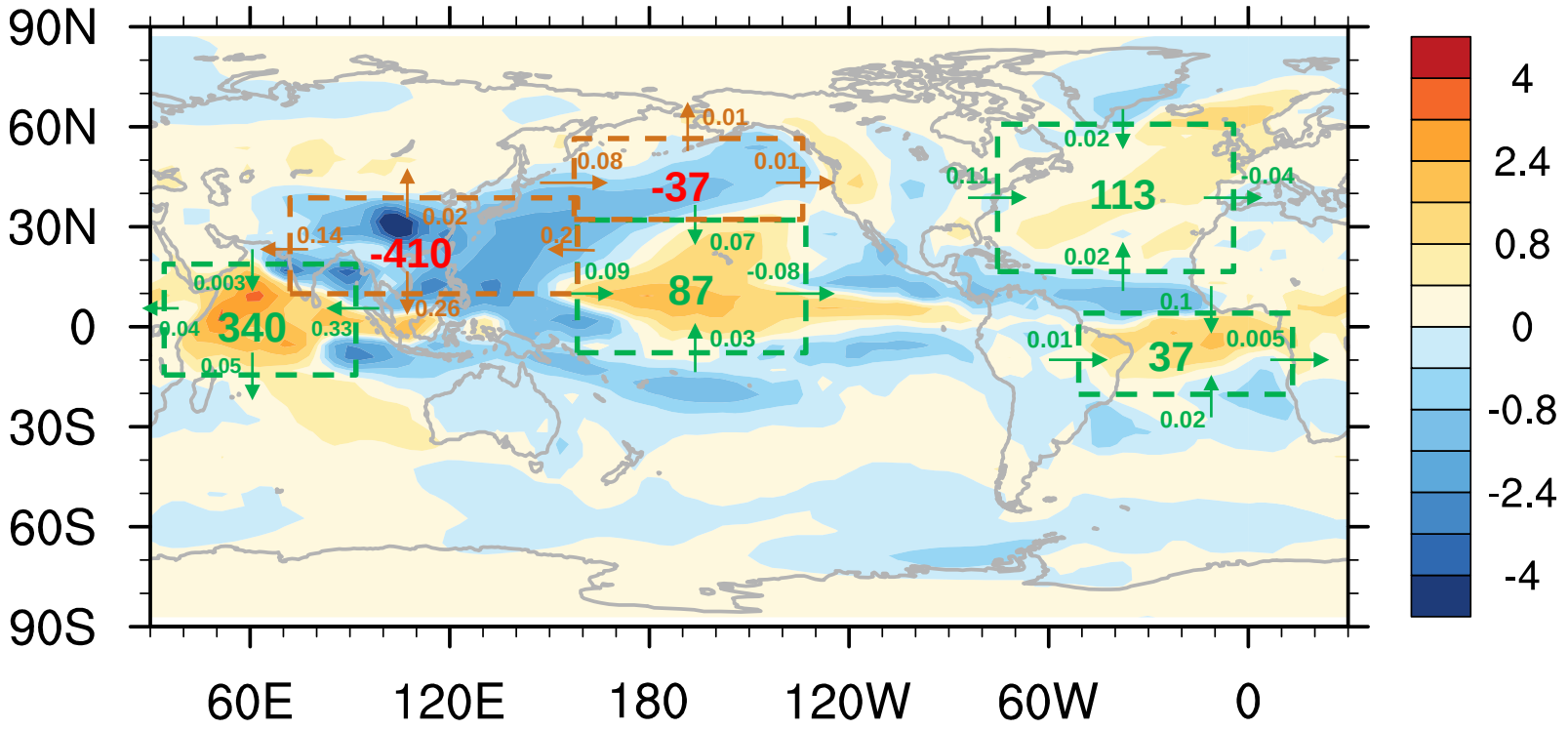
Rocky Mountain: No Role in MOC



Rocky Mountain: No Role in MOC

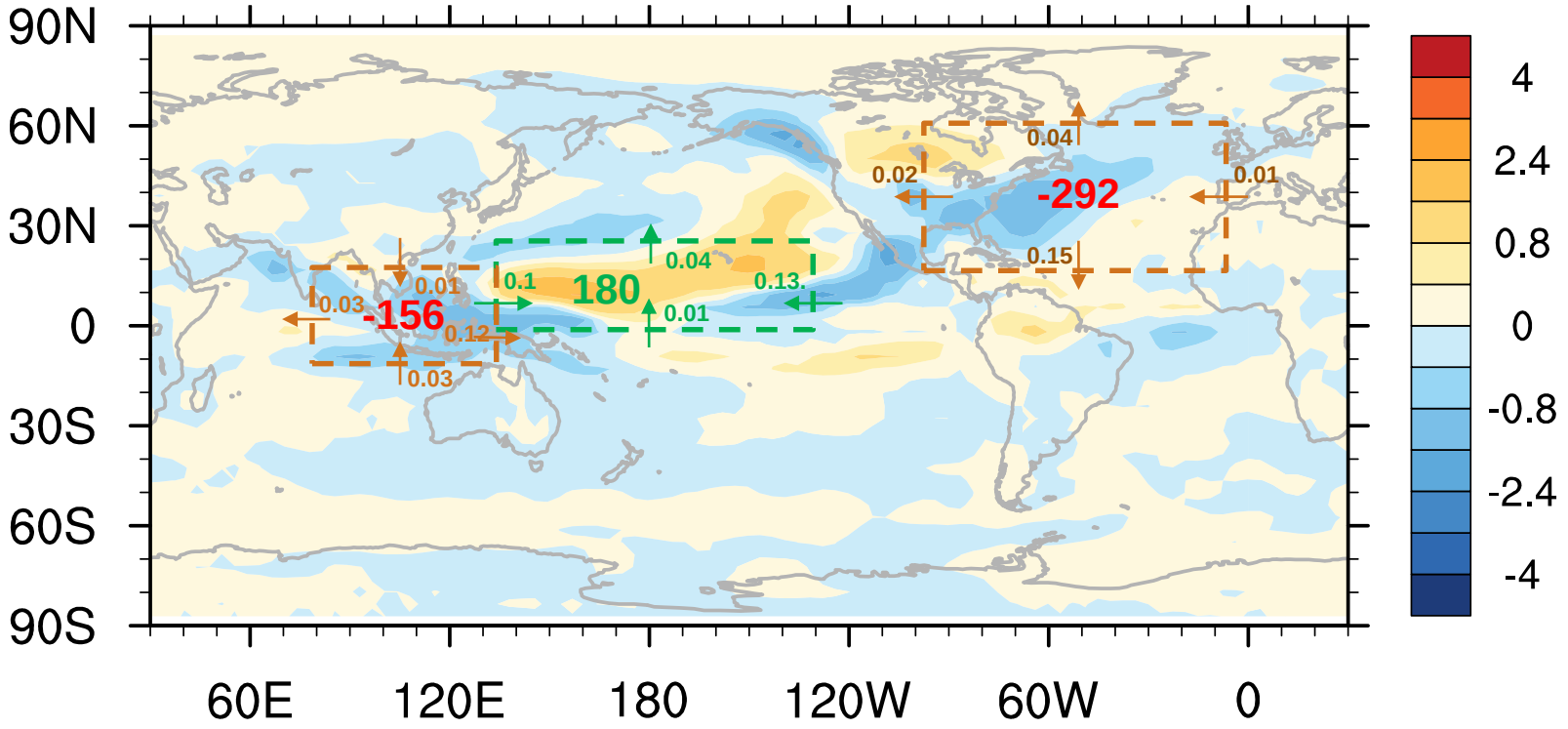


TP: Global Freshwater Budget



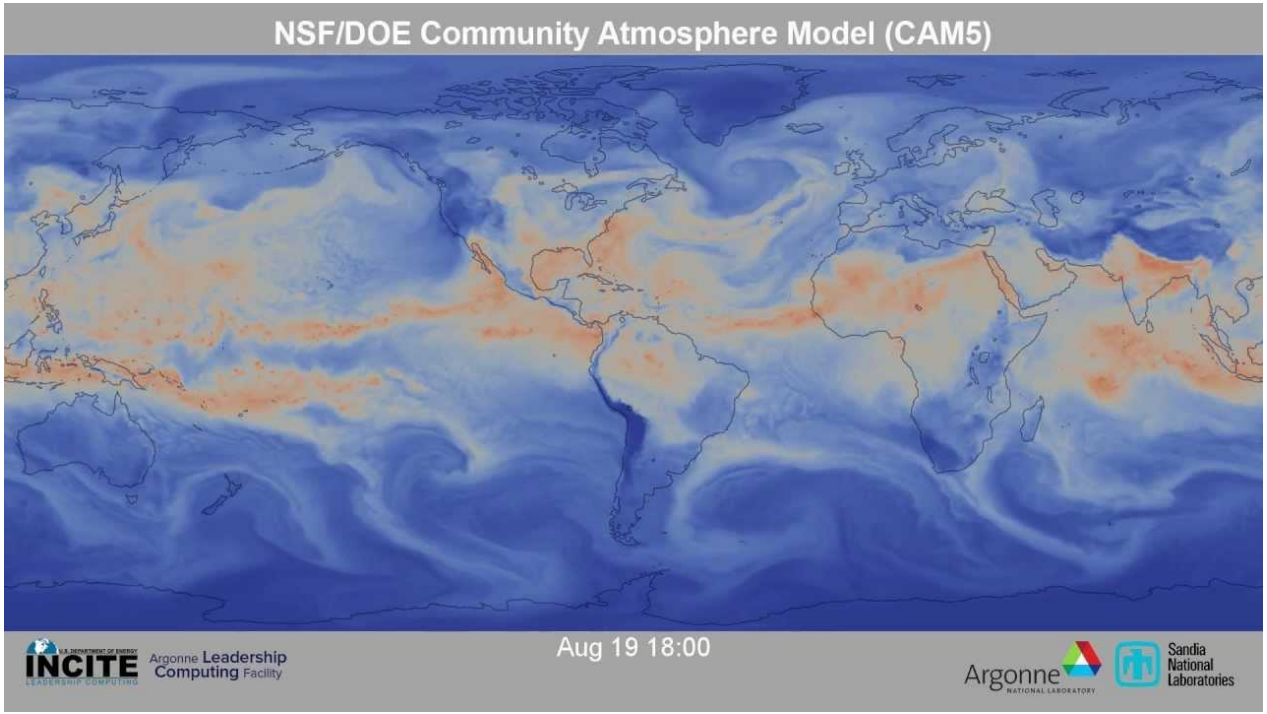
Water vapor transport across boundaries (Sv) and its convergence (mm/year)

RM: Global Freshwater Budget

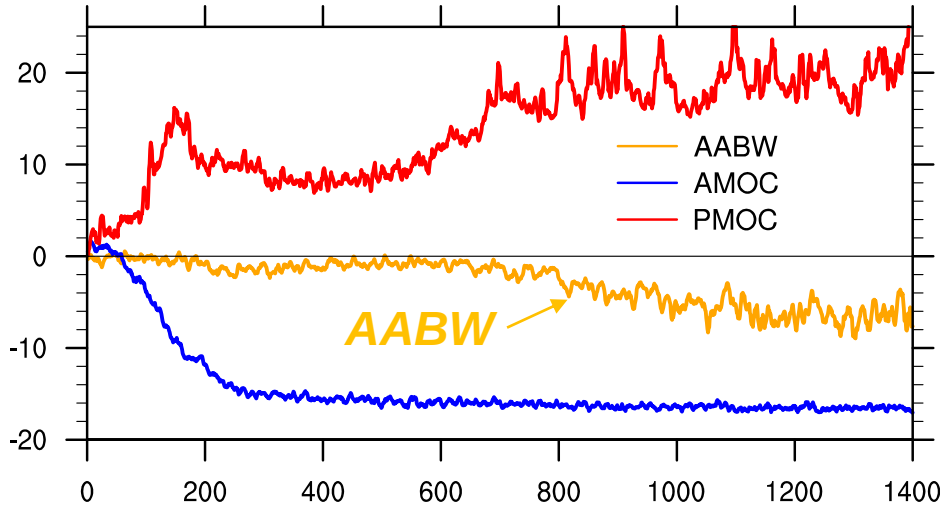


Water vapor transport across boundaries (Sv) and its convergence (mm/year)

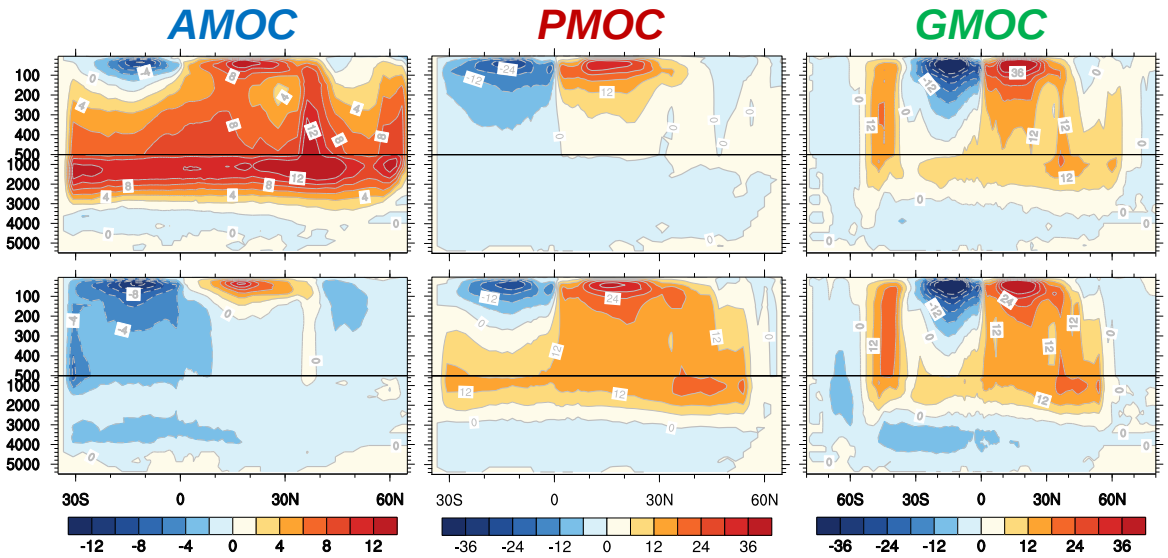
Atmosphere River



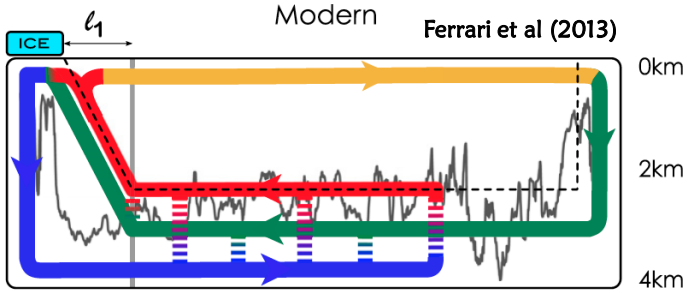
TP effect on *AABW*

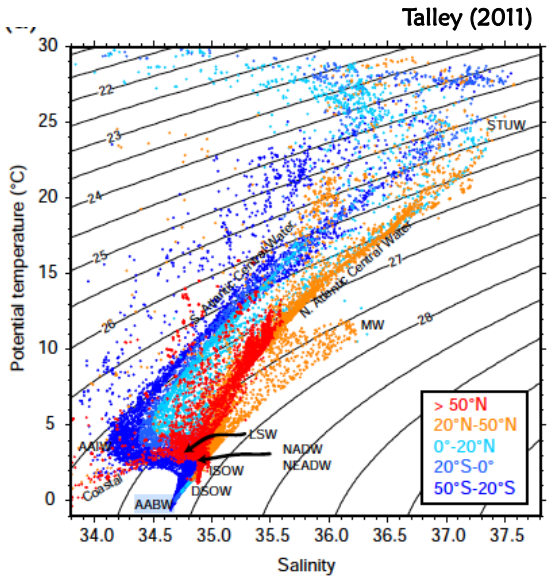


Global MOC


AMOC
PMOC
GMOC
Real
NoTibet
100
200
300
400
500
1000
2000
3000
4000
5000
30S
0
30N
60N
60S
-12 -8 -4 0 4 8 12
-36 -24 -12 0 12 24 36

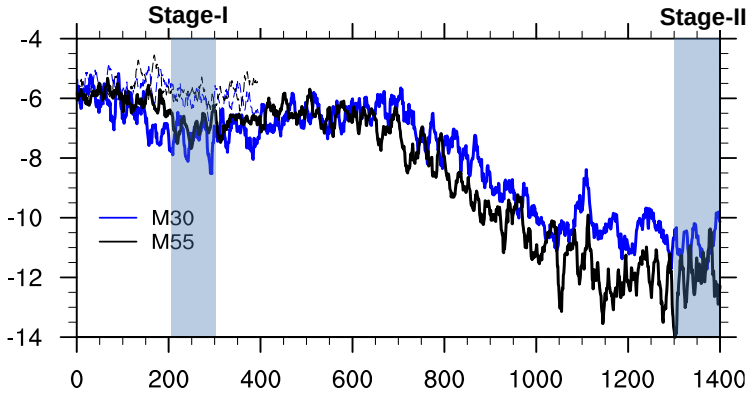
AABW: Background

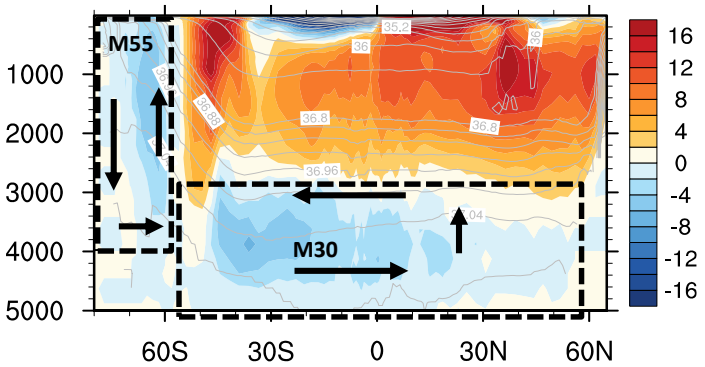




AABW is the coldest, densest water mass that occupies most of the world's deep basins, ventilating the lower limb of the meridional overturning circulation (MOC)

NoTibet : AABW Enhanced





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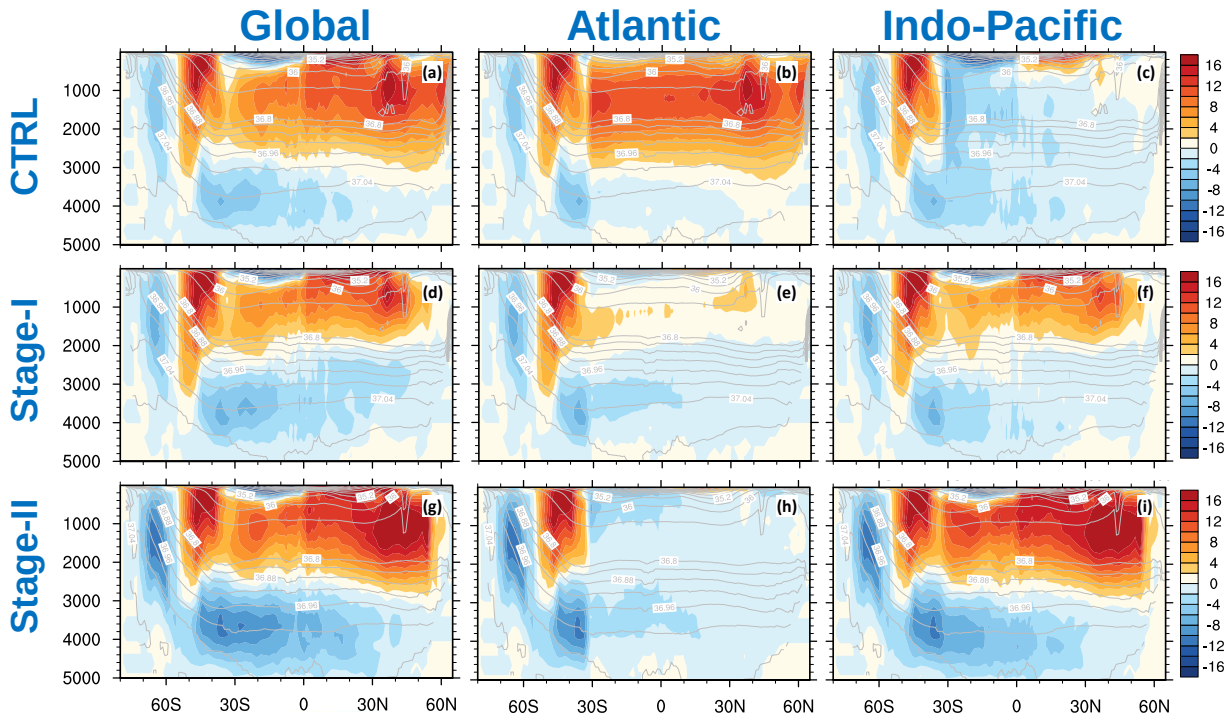
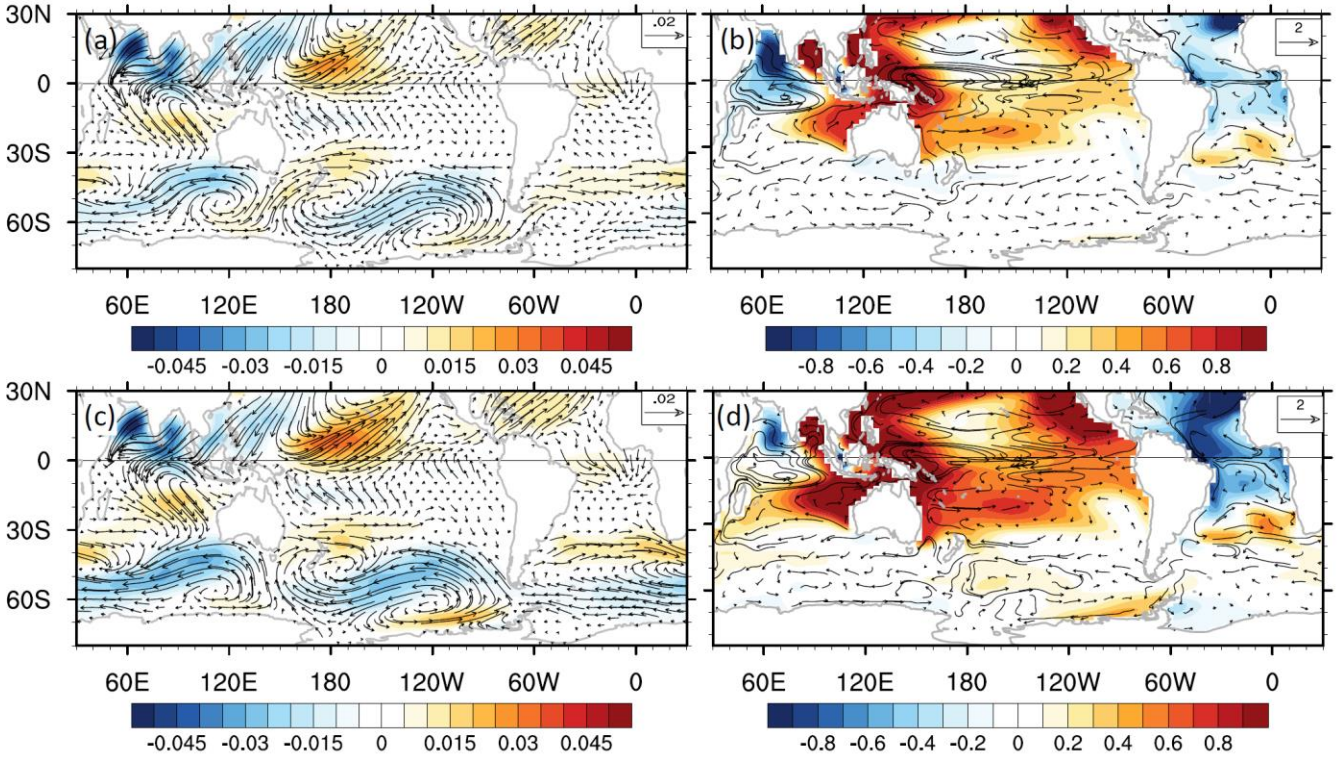
NoTibet: AABW Enhanced

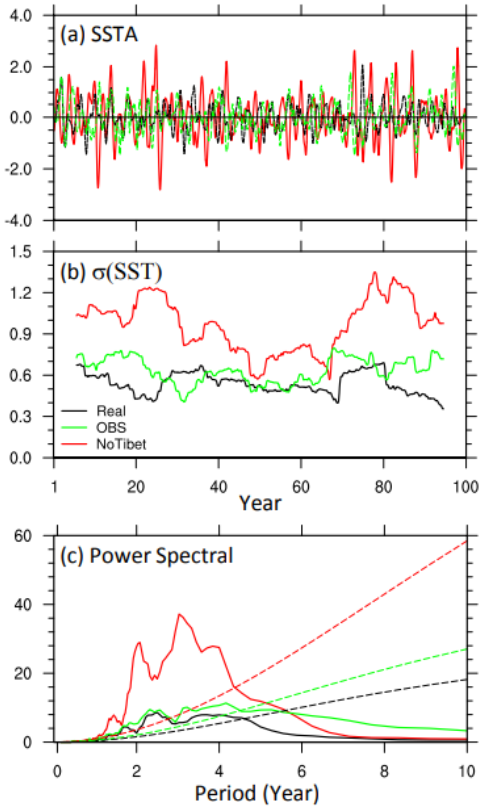


In Stage-I, the AABW is enhanced in Atlantic basin
In Stage-II, the AABW is also enhanced in Pacific basin

TP effect on *AABW*: Atmospheric Change



TP effect on ENSO



Amplitude: 80%⇑

Period: unchanged

Wen, Q., K. Doos, Z. Lu, Z. Han, and **H. Yang**, 2019: Investigating the role of the Tibetan Plateau in ENSO variability. *J. Climate*, doi: 10.1175/JCLI-D-19-0422

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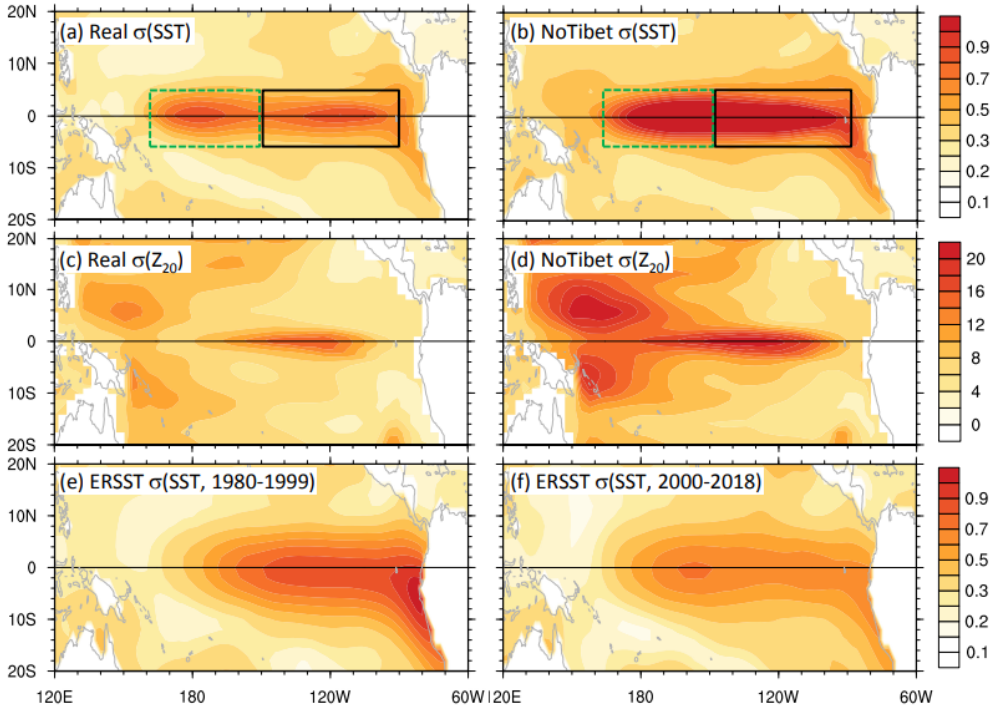
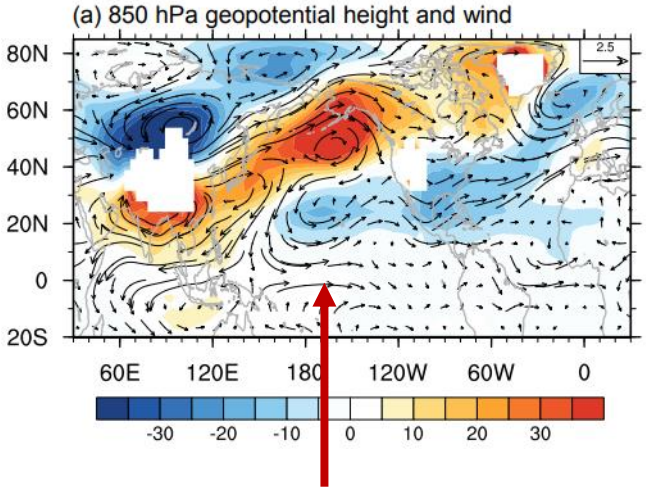
ENSO Pattern



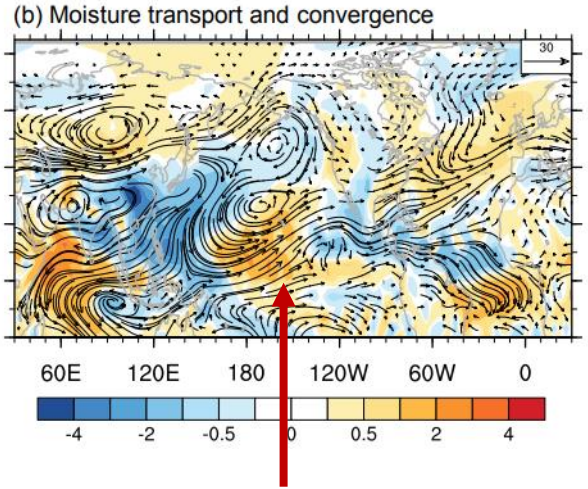
- 没有青藏高原，ENSO变率显著增强！

Mean Climate Change in Tropical Atmosphere

850hPa 位势高度 & 风

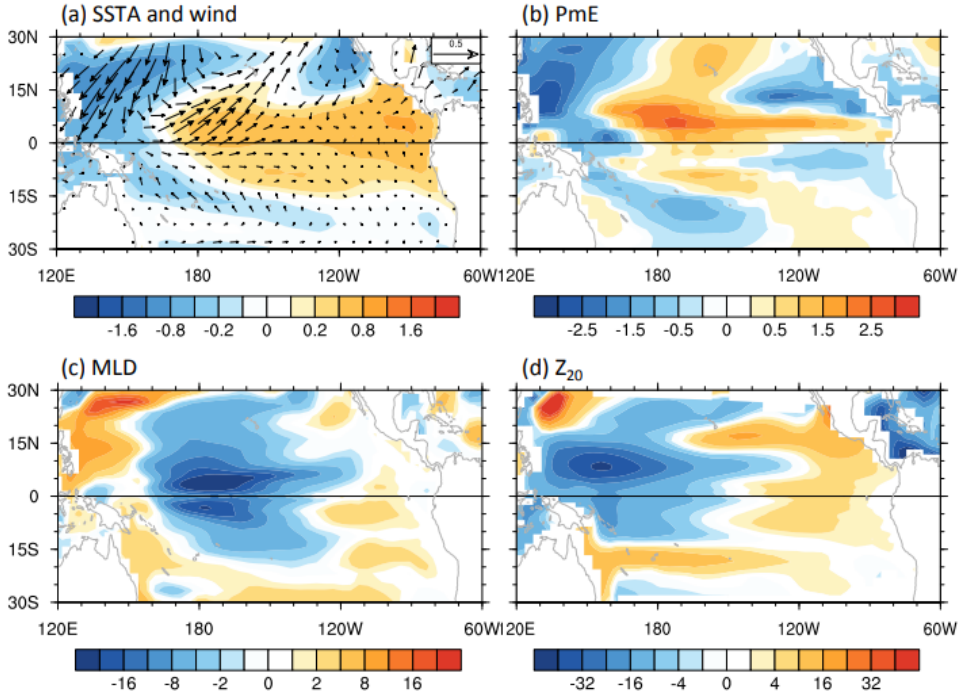


水汽输送&辐合辐散



- **热带太平洋信风减弱；**
- **水汽在赤道中太平洋辐合**

Mean Climate Change in Tropical Ocean



- 热带太平洋信风减弱
- El Nino型海温异常
- 混合层变浅
- 温跃层变平

Mechanism: Diagnosis Method

$$\frac{\partial[\sigma^2(t)]}{\partial t}$$

温度变率：

$$\sigma^2(t) = \frac{1}{N-1}\sum_{t-\frac{N}{2}}^{t+\frac{N}{2}} T'^2(t)$$

$$= \frac{2}{N-1}\sum_{t-\frac{N}{2}}^{t+\frac{N}{2}} [(\underbrace{-\bar{u}T'T'_x - u'T'\bar{T}_x - u'T'T'_x}_{\text{u方向平流}}) + (\underbrace{-\bar{v}T'T'_y - v'T'\bar{T}_y - v'T'T'_y}_{\text{v方向平流}})$$

$$+(\underbrace{-\bar{w}T'T'_z - w'T'\bar{T}_z - w'T'T'_z}_{\text{w方向平流}}) + \underbrace{A_h T'T'_{xx}}_{\text{水平扩散}} + A_h T'T'_{yy} + \underbrace{T'Q'_F}_{\text{垂直扩散}} + T'R'_E]$$

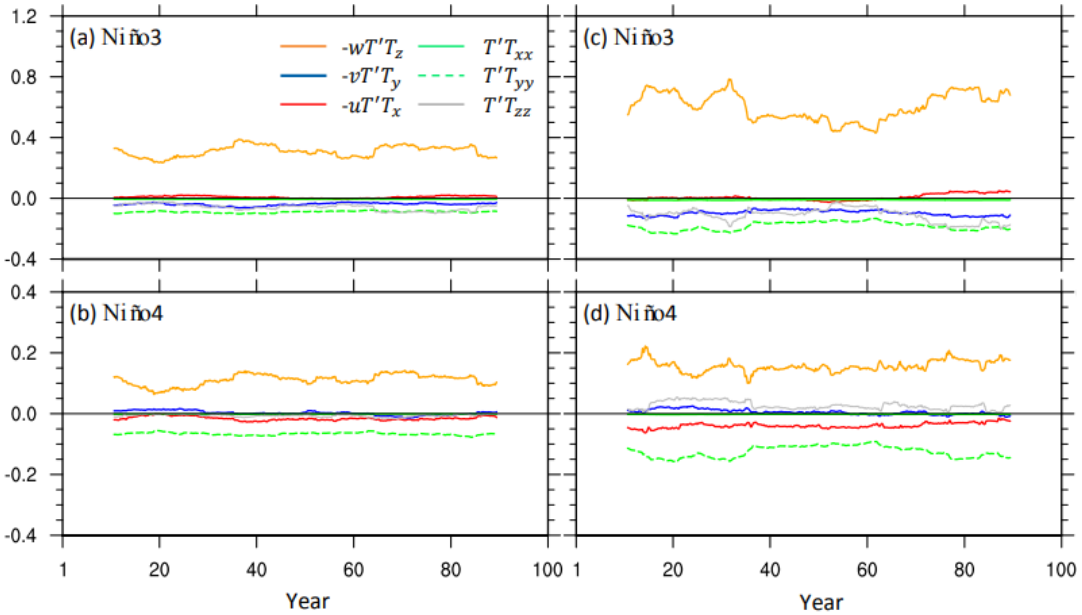
Yang, H., and Q. Zhang, 2008: Anatomizing the ocean role in ENSO changes under global warming. *J. Climate*, **21**, doi: 10.1175/2008JCLI2324.1, 6539-6555.

Diagnosis Results

有TP　　无TP

Nino3

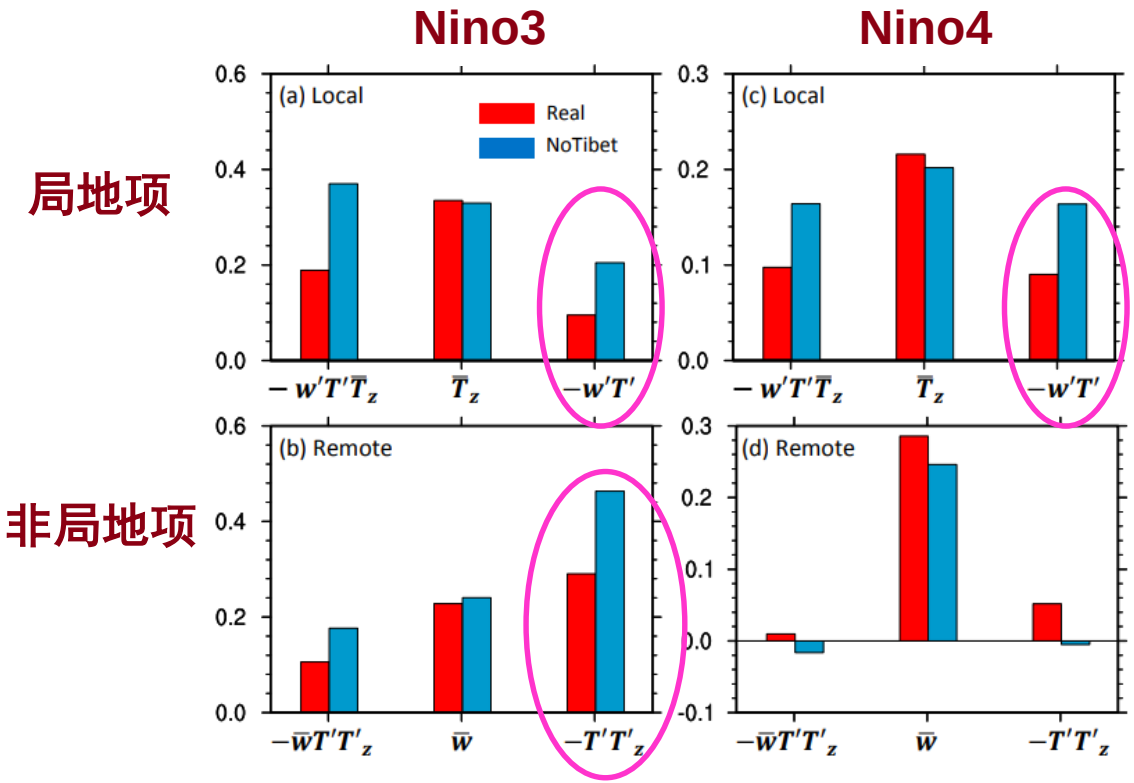
Nino4



- 没有青藏高原，ENSO变率增加由垂直平流项主导！

Diagnosis Results

垂直平流＝非局地项（ $-\overline{w}T'T'_z$ ）＋局地项（ $-w'T'\overline{T}_z$ ）



Local Term

局地项：$-w' = \beta_w \mu_a T'$ ； $(\tau'_x = \mu_a \langle T' \rangle, \quad w' = -\beta_w \langle \tau'_x \rangle$

μ_a：风应力对海表温度扰动敏感性； β_w： 海洋对海表风应力扰动敏感性

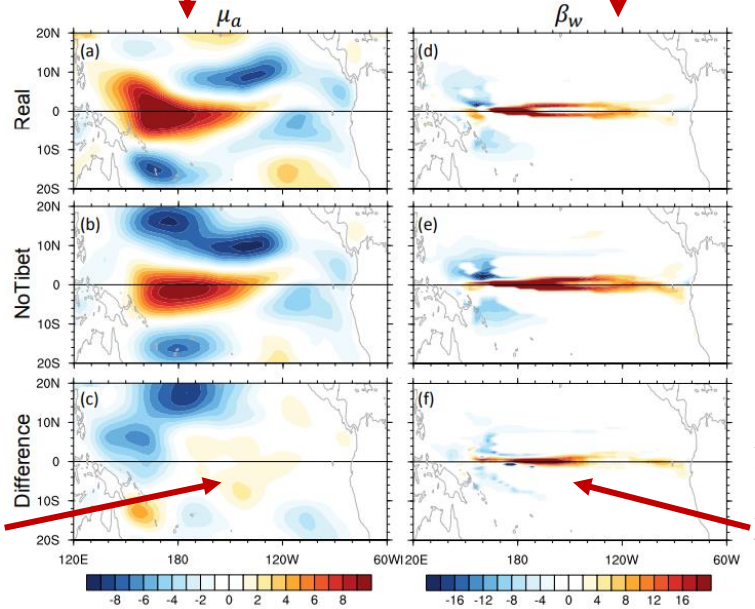
有TP

无TP

无TP - 有TP

大气敏感性东移：

深对流东移



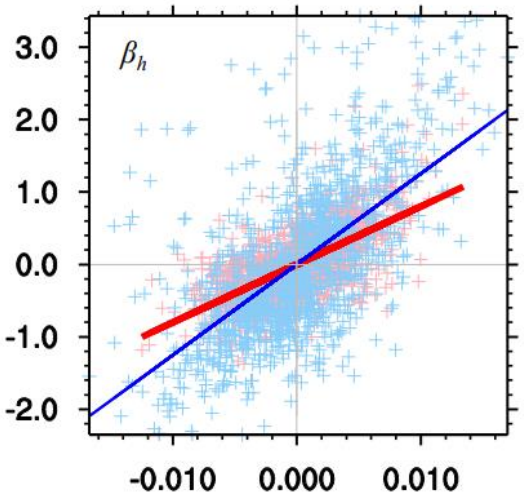
海洋敏感性增强：

混合层变浅

Remote Term

非局地项： $-T'_z = \frac{a\beta_h[\tau'_x]}{H} = \frac{a\beta_h\mu_a\langle T\prime\rangle}{H}$

β_h：海洋温跃层倾斜度对海表风应力扰动敏感性



海洋温跃层变平，温跃层倾斜度; 对海表风应力扰动敏感性增加

Red for Real, Blue for NoTibet

Summary

0 → 1 : TP is critical to AMOC, PMOC, by regulating the energy and moisture transport in / between SH and NH

1 → ∞ ……

LaCOAS
北京大学气候与海-气实验室

谢 谢

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