连接青藏高原与南北极：季节与路径

Connecting Tibetan Plateau to Arctic and Antarctic

Seasonality and Passage

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Tibetan Plateau (TP): the 3rd Pole

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

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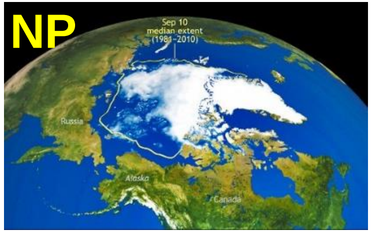
A Fundamental Question: *With* / *Without* TP



- 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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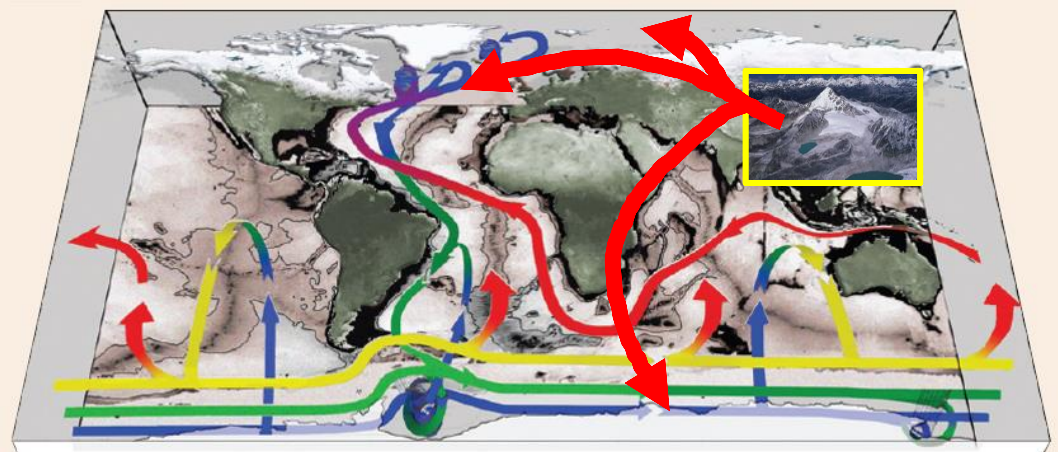
TP: A *Global* Perspective

How and to what extent?



Marshall et al., Nature (2012)

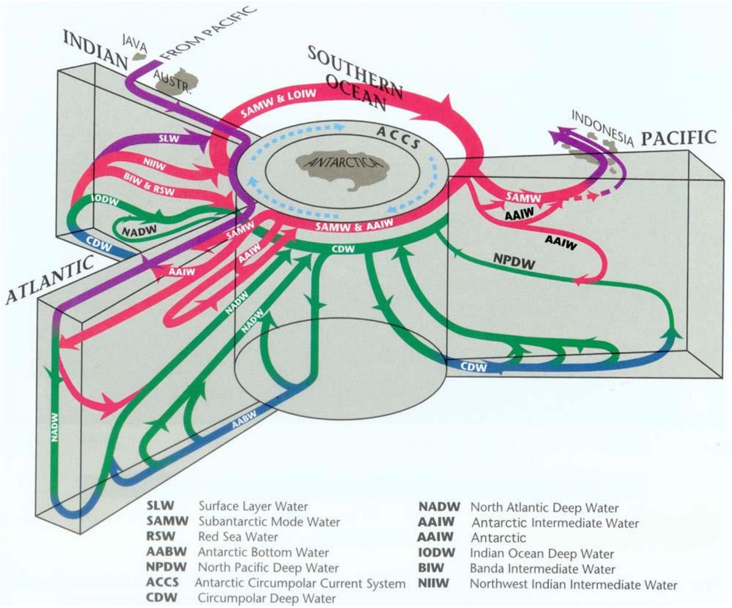
TP → NH vs. SH Asymmetry → Energy & Hydrological Cycle → Wind & Freshwater → Global Conveyor Belt

Global Meridional Overturning Circulation

Energy and Freshwater Balance

Weak

AMOC

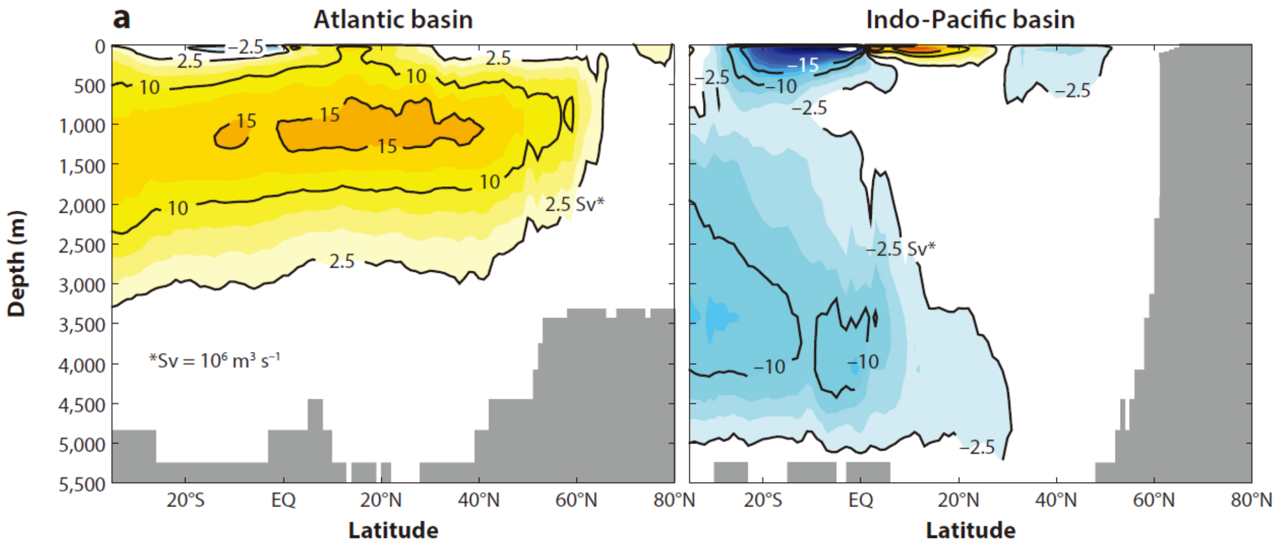


PMOC

Schmitz (1997) Overturning circulation: Southern Ocean View

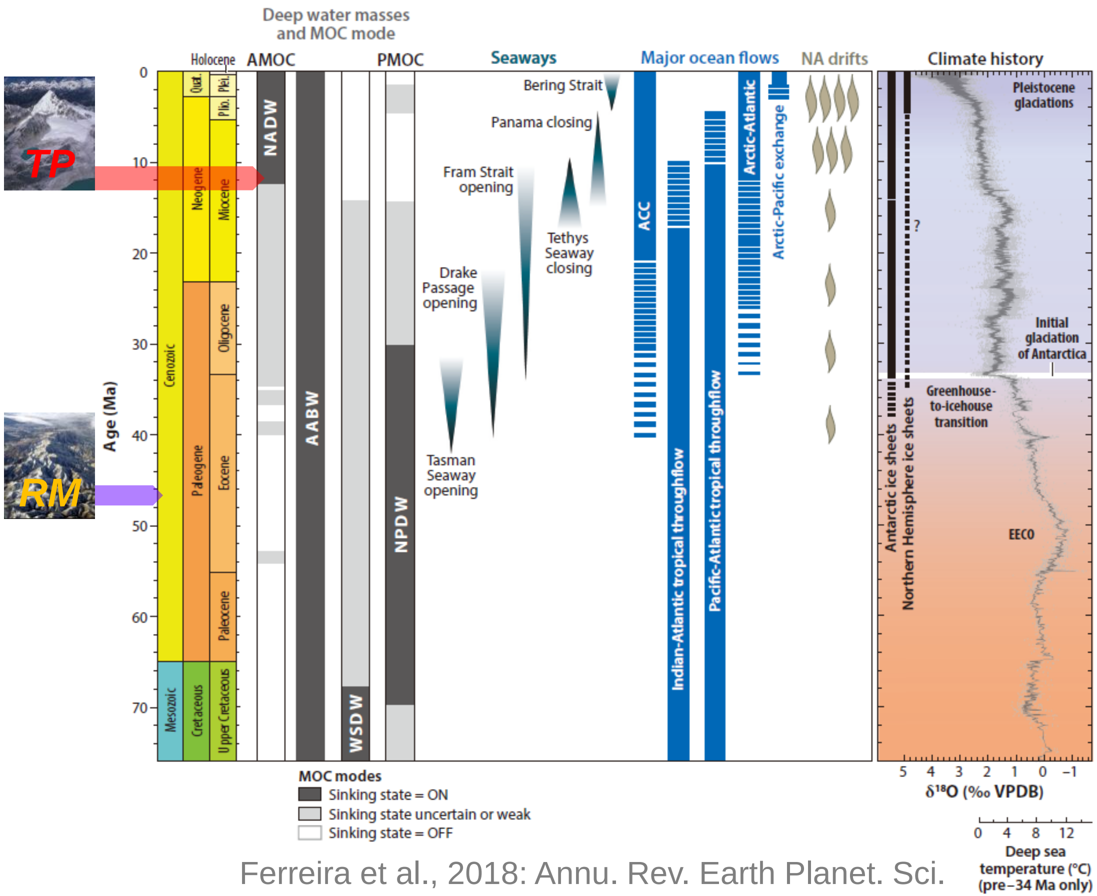
GMOC Now

Strong AMOC　　Weak PMOC



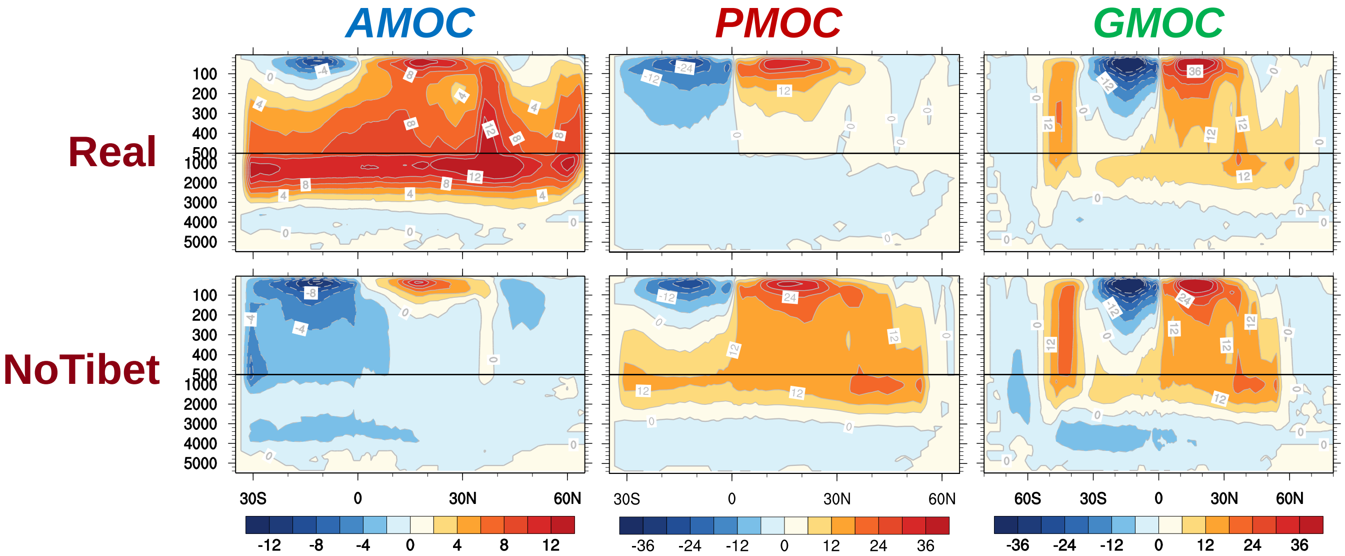
Ferreira et al., 2018: Annu. Rev. Earth Planet. Sci.

Geological History of *GMOC*



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

Global MOC



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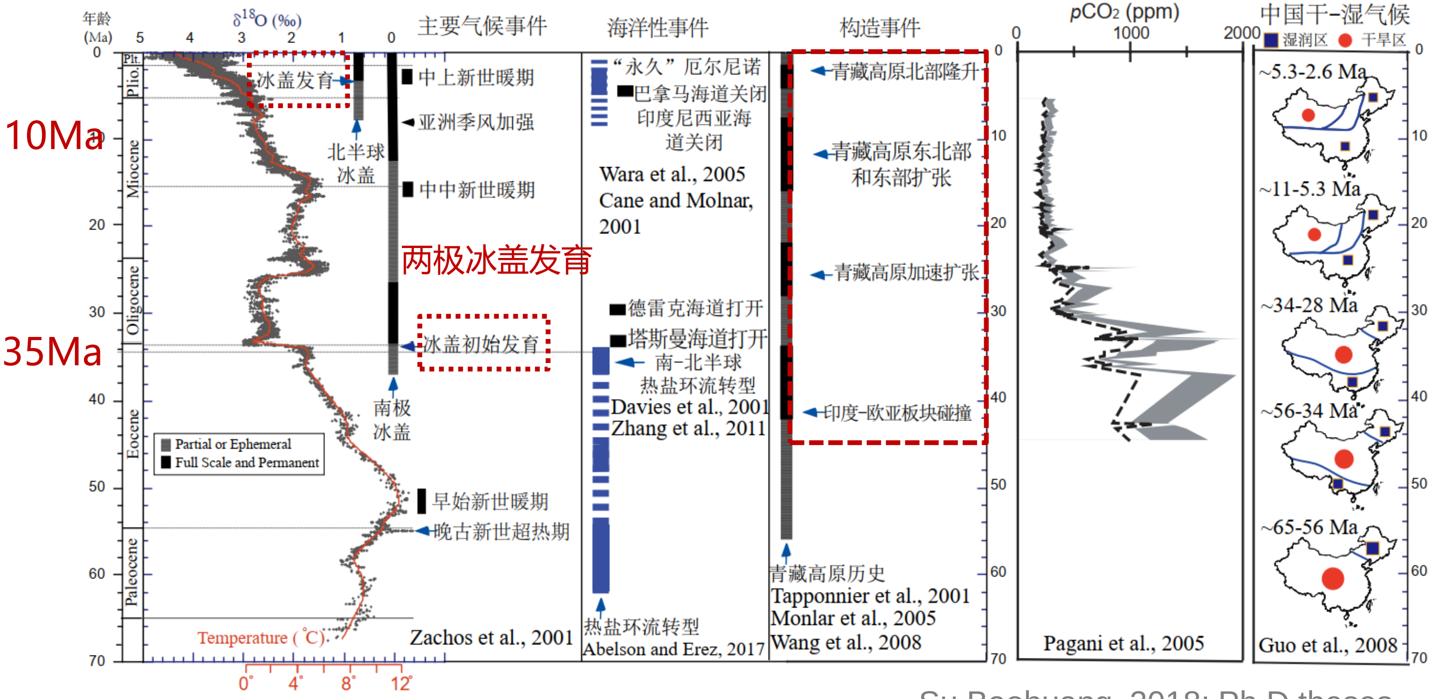
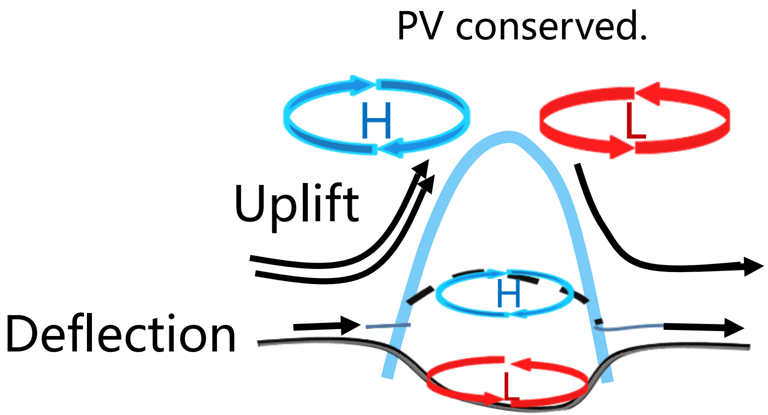
Geological History of Significant Events

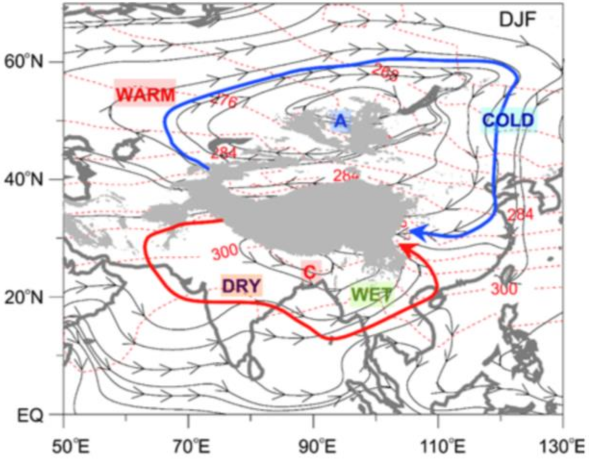


Su Baohuang, 2018: Ph.D theses

- 新生代以来，全球气候发生了巨大的变化，山脉隆升被认为是长时间尺度气候变化的重要驱动因素
- 青藏高原的隆升对邻近区域气候的研究非常广泛，较少关注遥远的北极和南极

Dynamical Effect





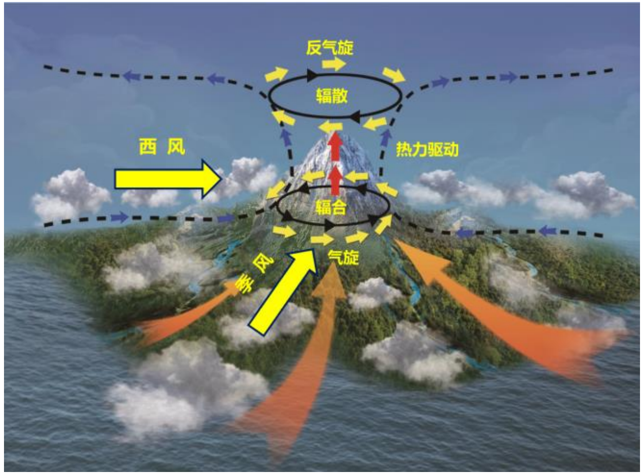
Wu et al. (2015)

低层绕流：
冷暖平流
干湿平流

- 低层绕流： “北脊南槽” ；中高层爬坡：迎风坡高压，背风坡低压
- 冬季：西风南移加强，TP位于西风带内；夏季：西风带北移，动力作用减弱
- 经过高原的背景气流有季节变化，高原对环流的影响有显著季节性差异

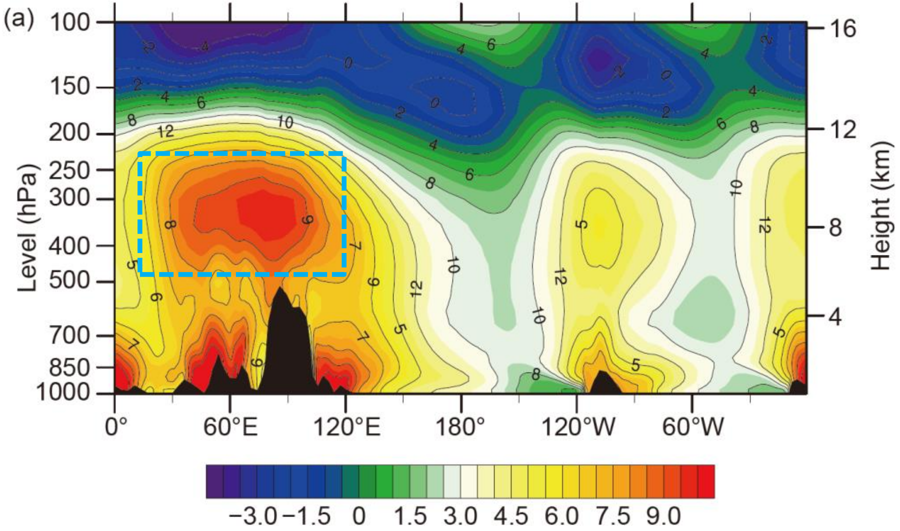
Thermal Effect

夏季热力作用示意图



- 夏季热源，冬季冷源
- 低层热低压，高层南亚高压

夏季27.5°~35°N东-西向气温纬向偏差垂直剖面图

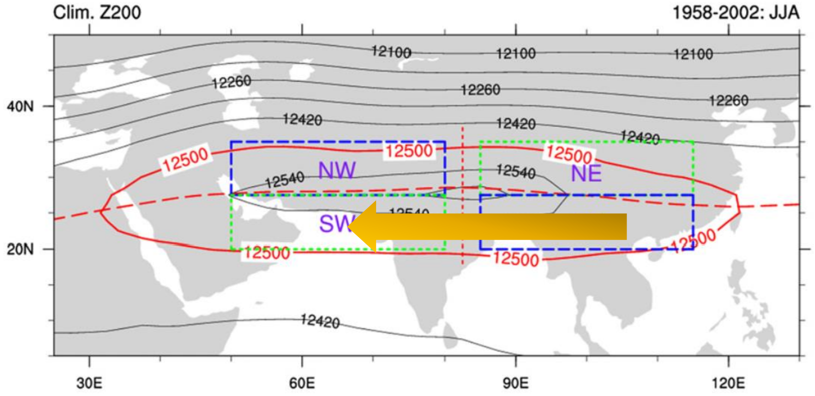


- 夏季热源可加热到高层自由大气

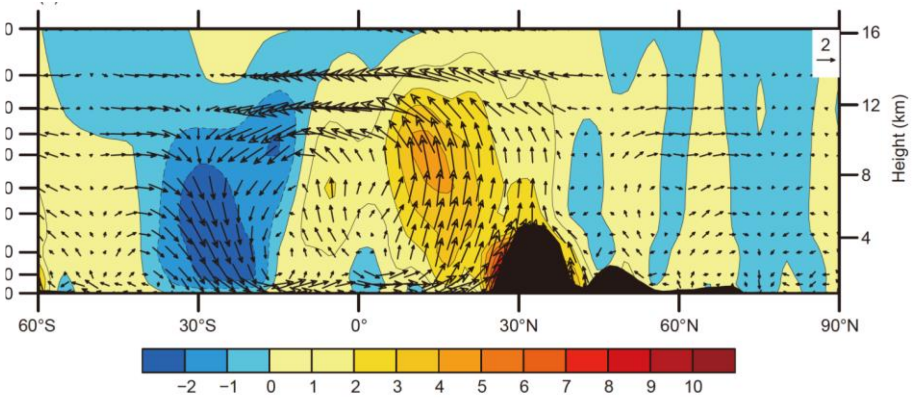
Xu et al. (2019)

Thermal Effect of TP

1958-2002年观测的200hPa位势高度



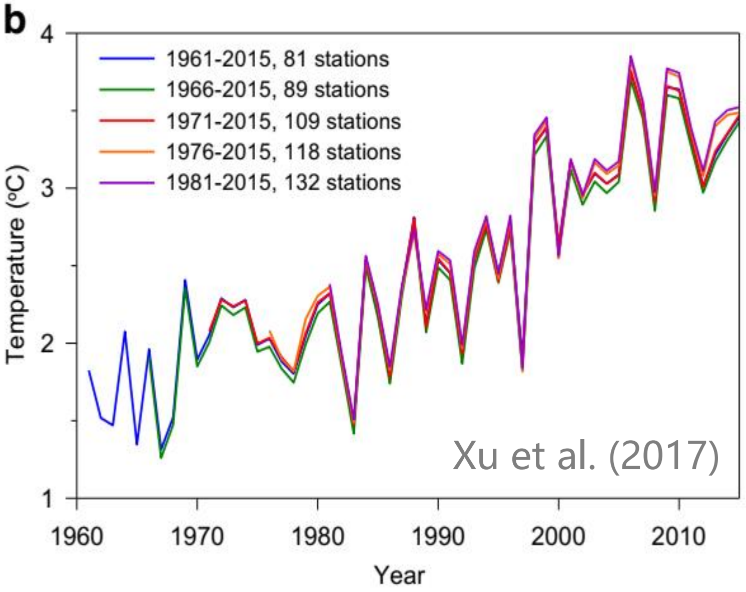
1948~2018年夏季80°~110°E平均经向风速(vector, m/s)和垂直速度 (color)



- 高层南亚高压，热带东风急流
- 经向反哈德莱环流，捕获水汽

Xu et al. (2019)

TP: Paleoclimatic and Modern Significance



0.35°C/decade in the recent 55 years

- 青藏高原区域对全球变暖非常敏感，远大于全球平均表面增温率，对全球气候产生强反馈
- 大气过程迅速持久，未来气候变化下，青藏高原的异常如何影响两极地区

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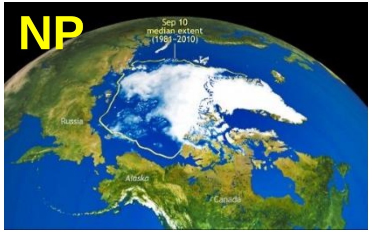
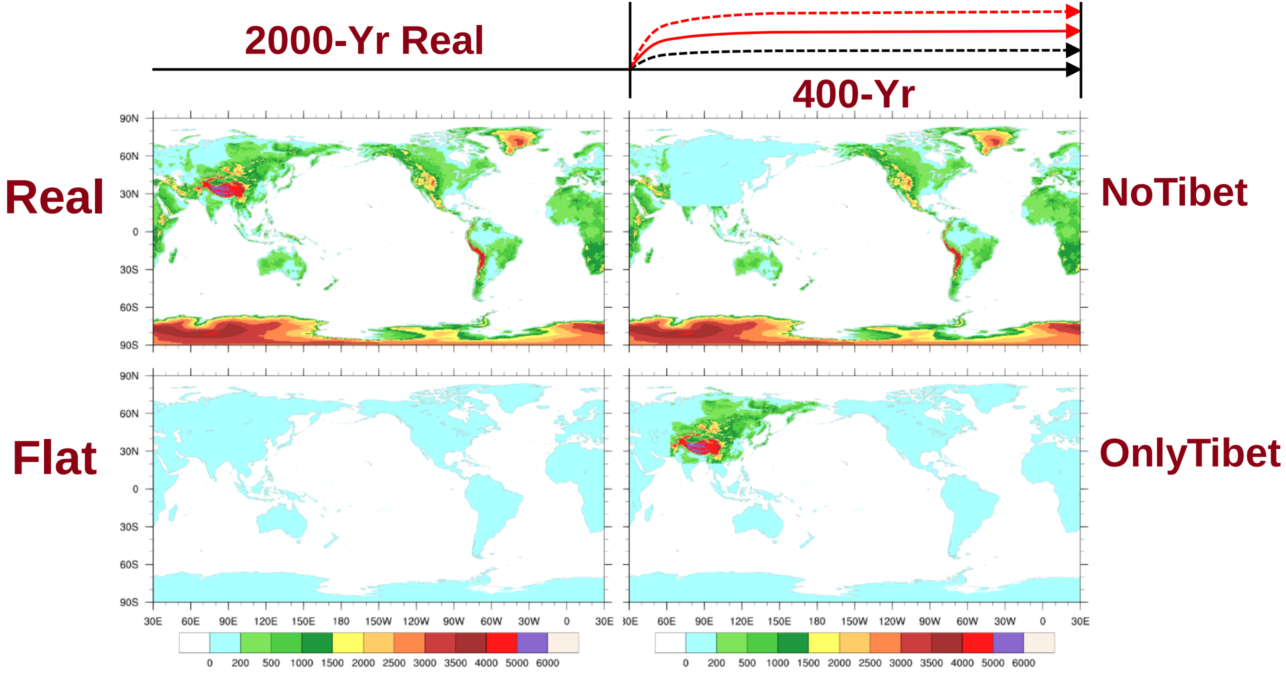
Fascinating Question: NP ⇔TP⇔SP



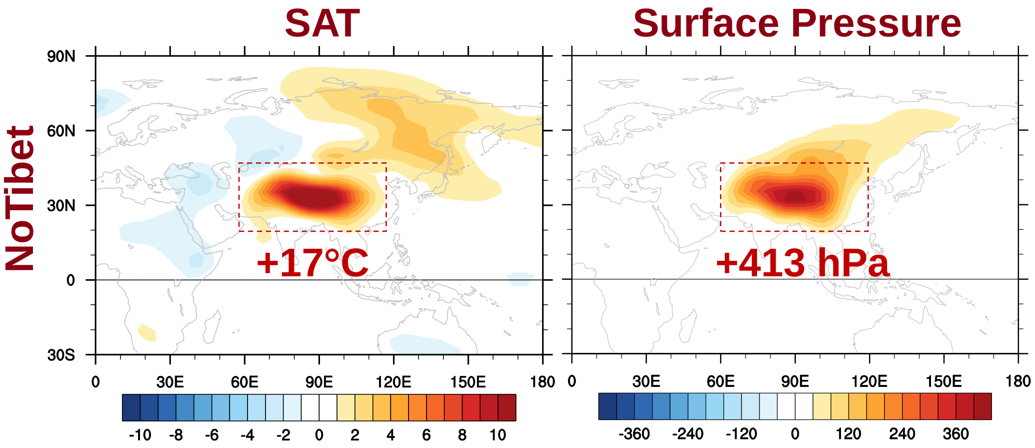
Seasonality, Passage and ***Mechanism ?***

Coupled Model Experiments *With* / *Without* TP



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

TP Forcing: *Thermal* and *Dynamical*



Lapse Rate T **~ 4 km x 7 ~ 28°C**

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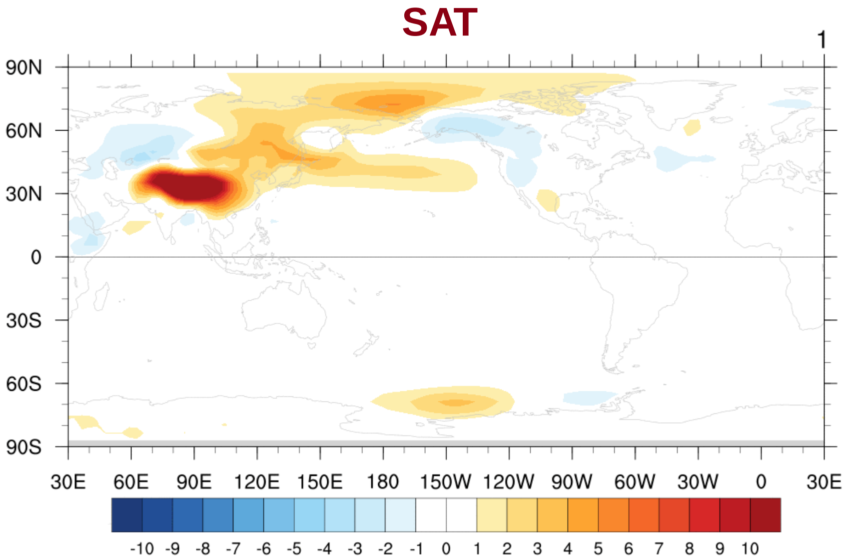
SAT Evolution w/o TP



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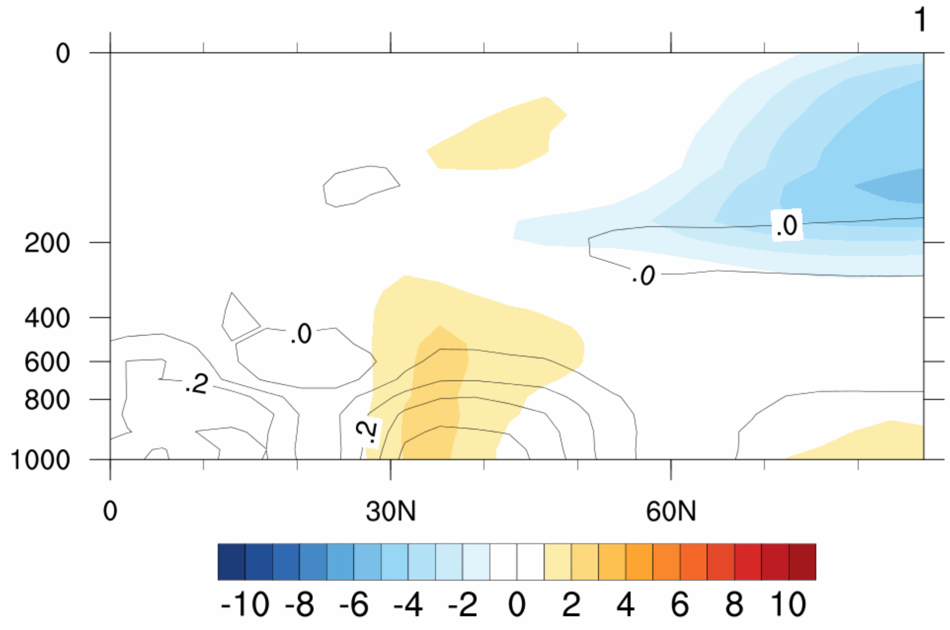
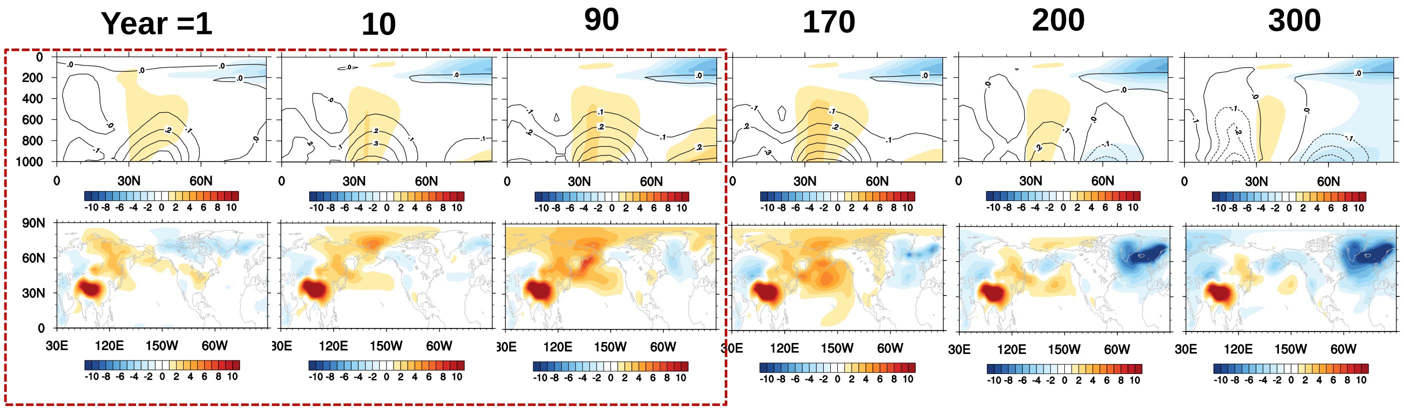
Atmosphere T and Moisture in NH



Transient Atmosphere T and Moisture in NH

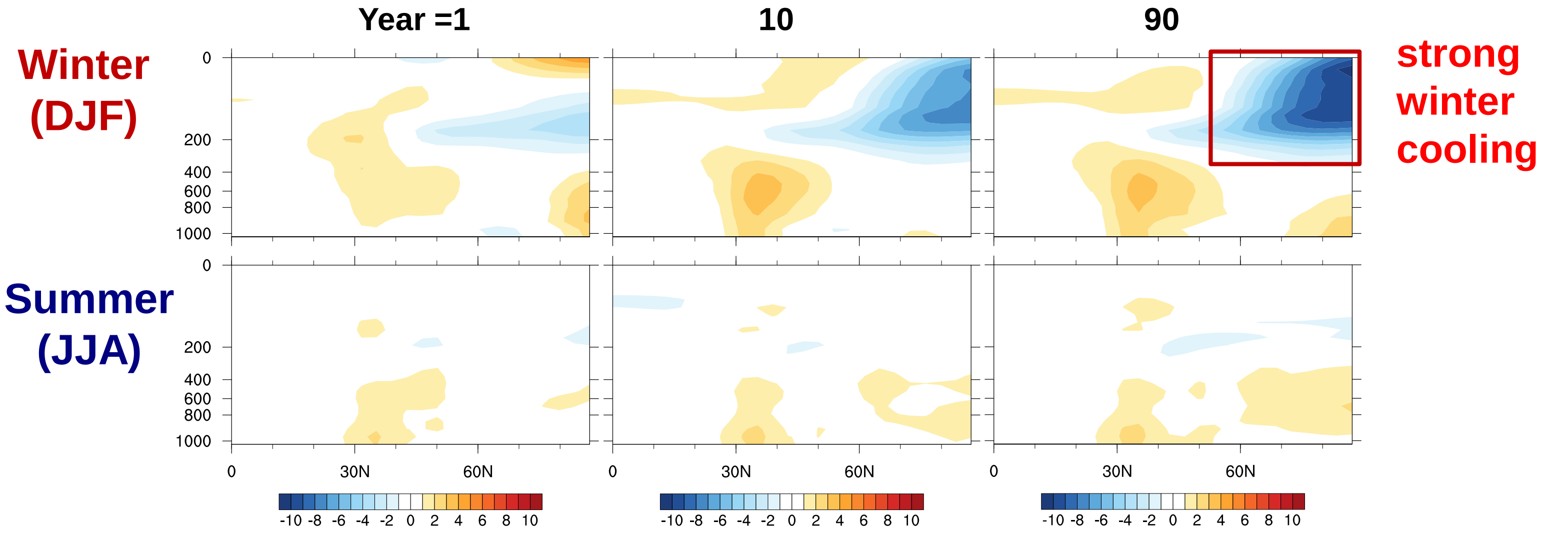
NoTibet → Arctic upper cooling lower warming



Atmospheric process

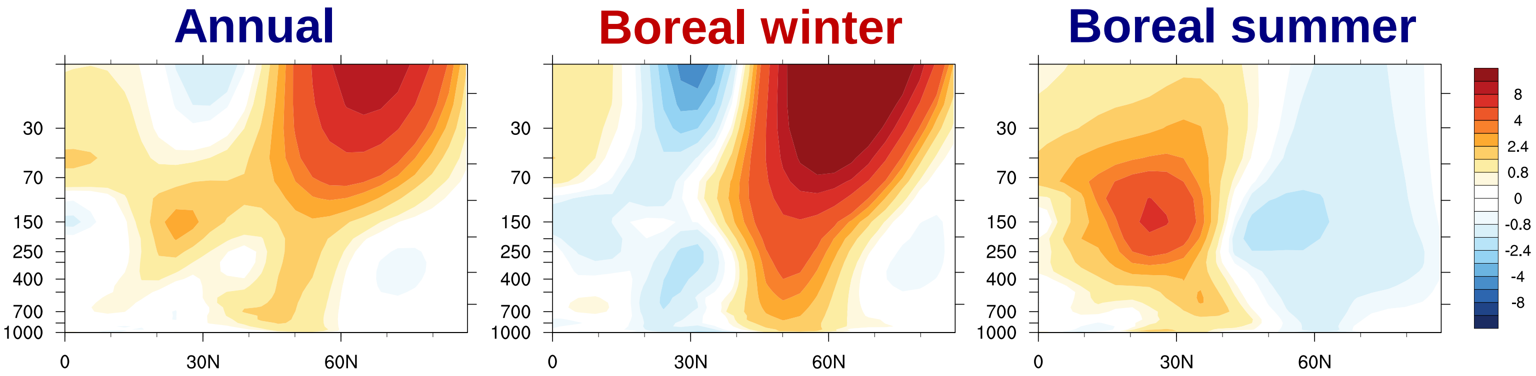
Ocean adjustment

Transient Atmosphere T and Moisture in NH



From TP to Arctic: Seasonality

Winds Change in NH



Background Planetary Winds

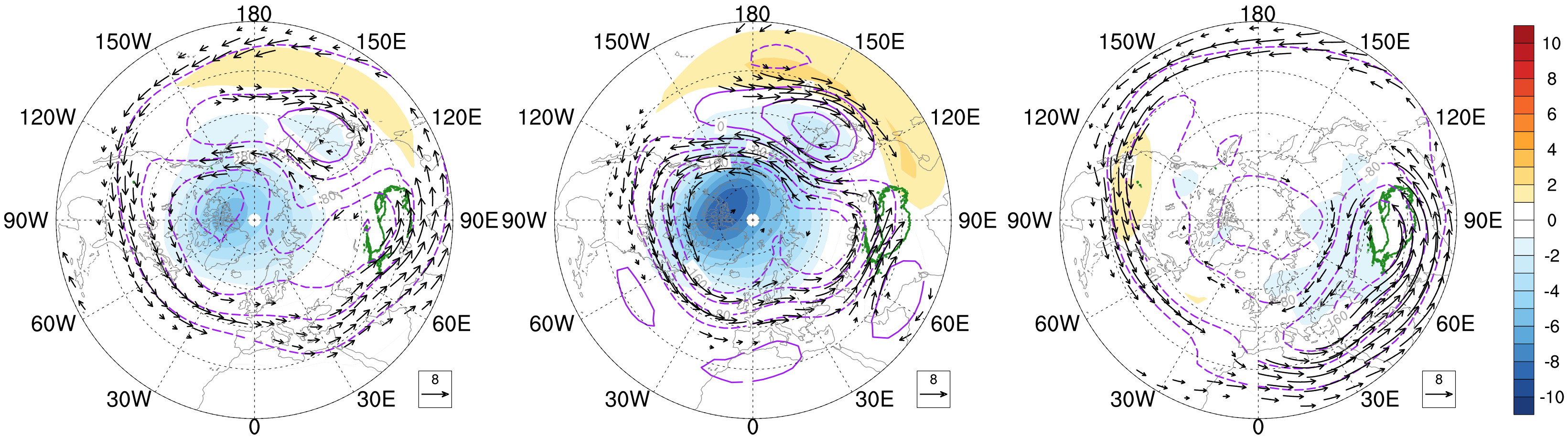
winter → **Expands southward** → **TP in westerlies** → **Westerlies ⇑**

NoTibet

summer → **Shrinks northward** → **TP in easterlies** → **Unchanged in high-latitudes**

Upper Circulation Change in NH

Annual | **Boreal winter** | **Boreal summer**



NoTibet ➡ **Winter Westerlies ⇑** ➡ **Polar Low ⇑** ➡ **Upper-level cooling**

Mechanism: *Wave Activity Flux*

NoTibet —Wave dynamics→ Higher-latitude Circulation

$$W=\frac{P\cos\Phi}{2|U|}\begin{bmatrix}\frac{u}{a^2\cos^2\Phi}\left[\left(\frac{\partial\Psi'}{\partial\lambda}\right)^2-\Psi'\frac{\partial^2\Psi'}{\partial\lambda^2}\right]+\frac{v}{a^2\cos\Phi}\left[\frac{\partial\Psi'}{\partial\lambda}\frac{\partial\Psi'}{\partial\Phi}-\Psi'\frac{\partial^2\Psi'}{\partial\lambda\partial\Phi}\right]\\ \frac{u}{a^2\cos\Phi}\left[\frac{\partial\Psi'}{\partial\lambda}\frac{\partial\Psi'}{\partial\Phi}-\Psi'\frac{\partial^2\Psi'}{\partial\lambda\partial\Phi}\right]+\frac{v}{a^2}\left[\left(\frac{\partial\Psi'}{\partial\Phi}\right)^2-\Psi'\frac{\partial^2\Psi'}{\partial\Phi^2}\right]\\ \frac{f_0^2}{N^2}\left\{\frac{u}{a\cos\Phi}\left[\frac{\partial\Psi'}{\partial\lambda}\frac{\partial\Psi'}{\partial z}-\Psi'\frac{\partial^2\Psi'}{\partial\lambda\partial z}\right]+\frac{v}{a}\left[\frac{\partial\Psi'}{\partial\Phi}\frac{\partial\Psi'}{\partial z}-\Psi'\frac{\partial^2\Psi'}{\partial\Phi\partial z}\right]\right\}\end{bmatrix}$$

Takaya and Nakamura (1997, 2001)

- Ψ' → perturbations created by the orography **(NoTibet minus Real)**
- **W directions** → directions of Rossby wave energy propagation ~ $\boldsymbol{C_g}$

$$\frac{\partial}{\partial t}M+\nabla\cdot\mathbf{W}=D_T$$

- **Divergence** → wave perturbation energy is emitted and converted to mean kinetic energy

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Mechanism: *Wave Activity Flux*

Wave Activity Flux — equal to → $-[(\mathrm{e}-v'v'), u'v', \zeta' P'_x]$

Takaya et al. (2001)

$$\mathrm{e} = \frac{1}{2}\left[u'^2 + v'^2 + \left(\frac{f_0}{N^2}\frac{\partial \Psi'}{\partial z}\right)^2\right]$$

Takaya et al. (2015)

equal to 2-D

$$E_u = \left[\frac{1}{2}(v'^2 - u'^2), -u'v'\right]\cos\Phi$$

Hoskins et al. (1983)

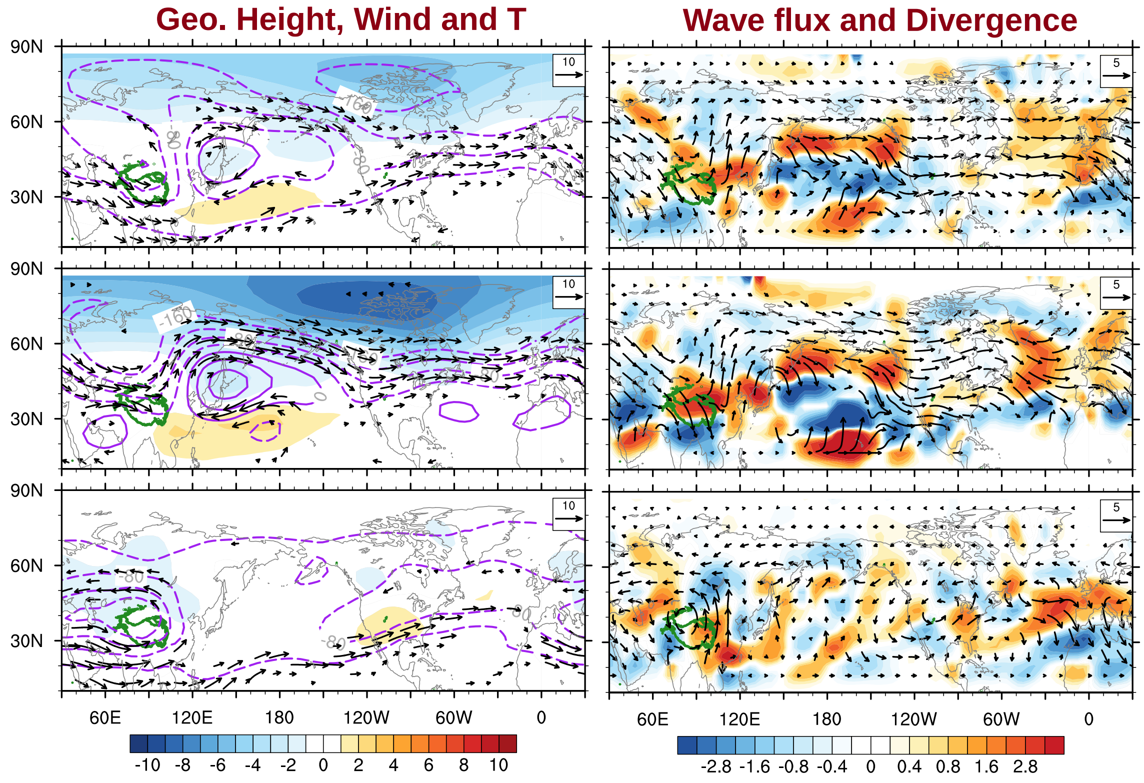
Applied to 2-D deep system

$$\frac{\partial \bar{u}}{\partial t} = \cos\Phi\,\nabla\cdot E_u$$

$$\frac{\partial}{\partial t}(\mathrm{PKE}) = -\frac{\partial}{\partial t}(\mathrm{KE}) = -\cos\Phi\cdot\bar{u}\nabla\cdot E_u$$

Simmons et al 1983)

Passage: *Planetary Wave* in Upper Level



Annual

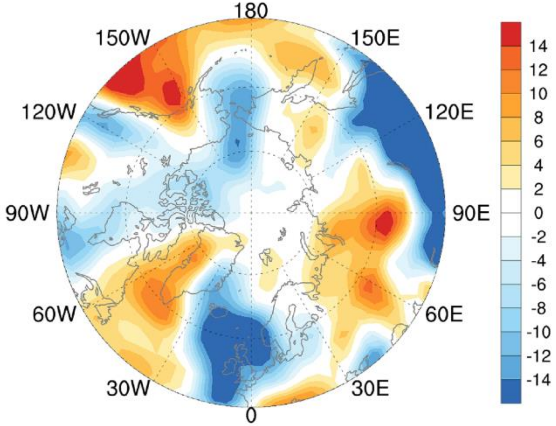
Boreal Winter

Boreal Summer

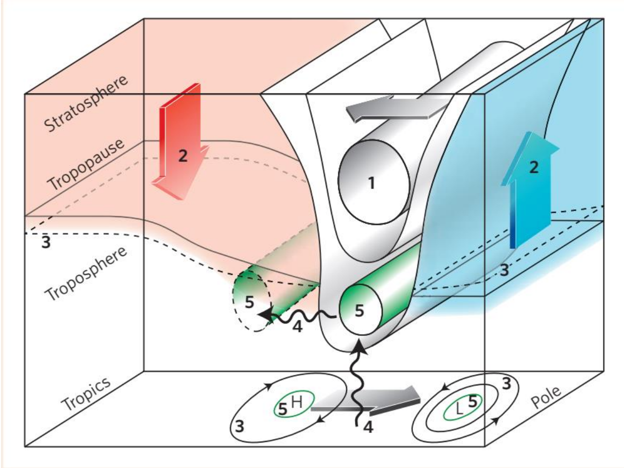
Northeastward by planetary flow

Locally trapped

Mechanism to *Polar Cooling* in Upper Level



Winter $\omega < 0$ ascending motion



Kidston et al. (2015) Review article
in Nature Geoscience

Stratosphere Westerlies ⇧ → **Polar Ascending** → **Adiabatic Cooling** → **Stratosphere Cooling**

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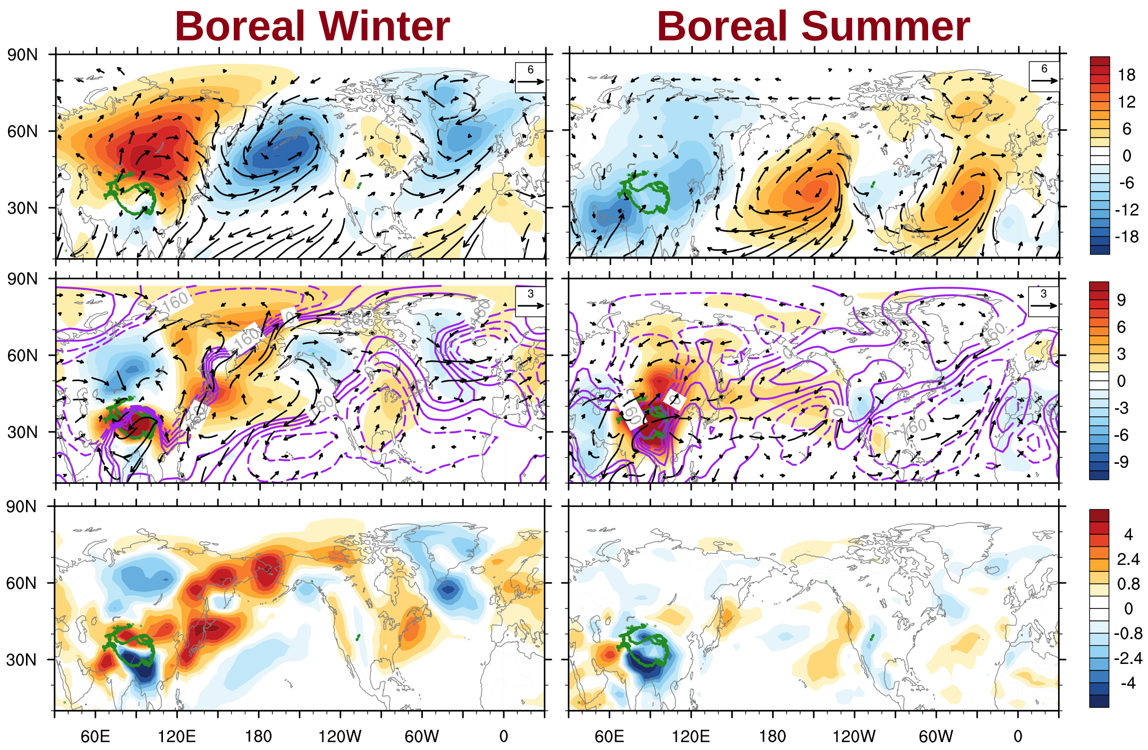
Passage: *Monsoon* in Lower Level

Wind and SLP for Real

SLP, wind and T

T advection



NoTibet

Heat advection warming Arctic

East-northward dominated by monsoon

Seasonality and Passage: *Background* Winds

TP-Arctic connection **Robust** in boreal winter:

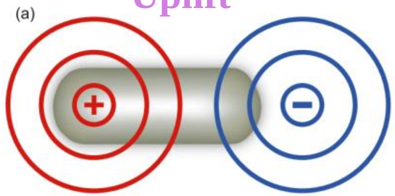
Seasonal variation of background winds

Upper

Westerlies → Eastward wave energy propagation

Easterlies → Locally trapped

Uplift



Holton (2004)

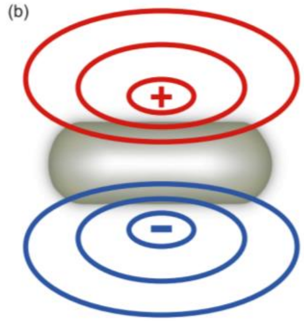
Forced topographic wave solution

Lower

$$\phi_n = \frac{f_0{}^2 h_n}{gH(K^2 - K_s{}^2 - irK^2/k\bar{u})},$$

Wave amplitude ∝ U

Deflection



Held et al. (1983)

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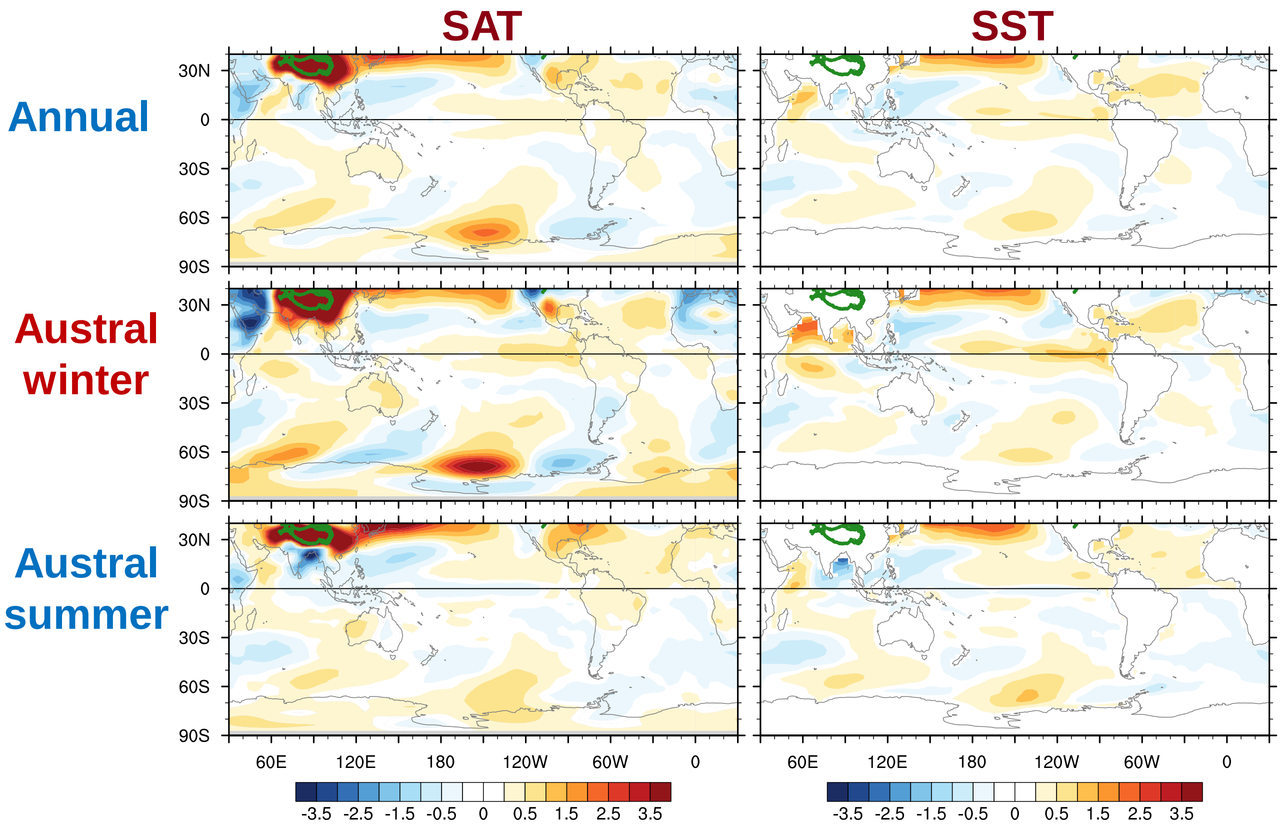
Temperature Change in the SH

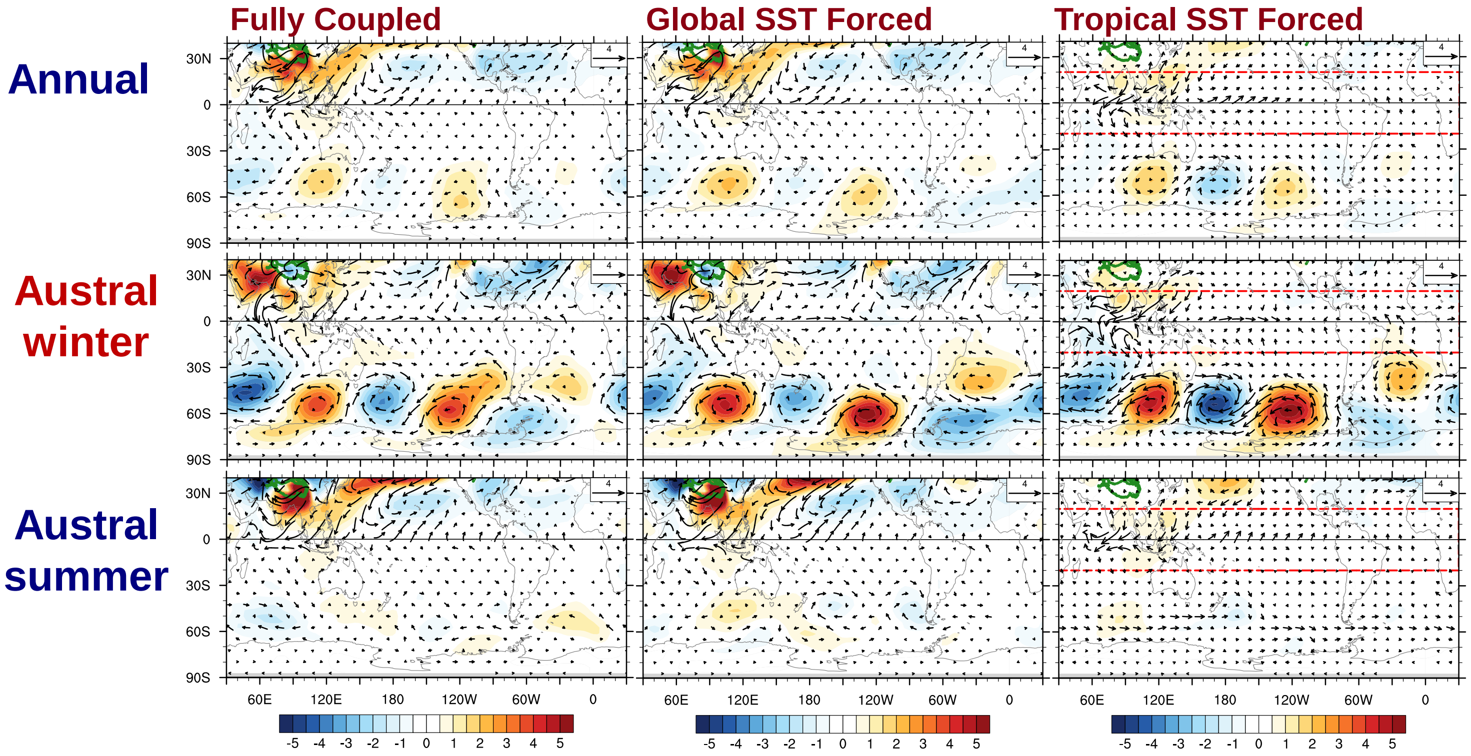


NoTibet

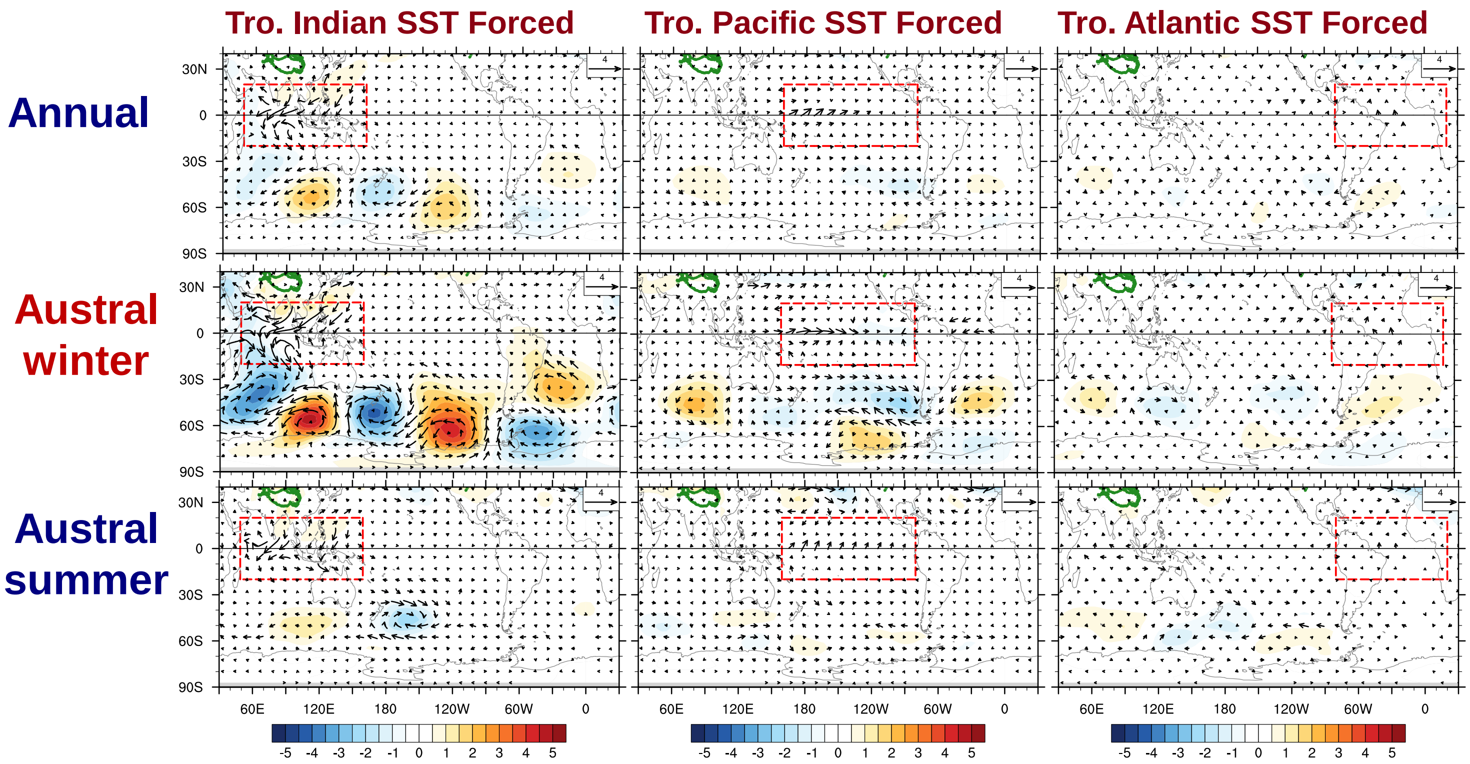
Antarctic Rossby-wave like T change

Seasonality and Passage

NoTibet → Wave-5 pattern

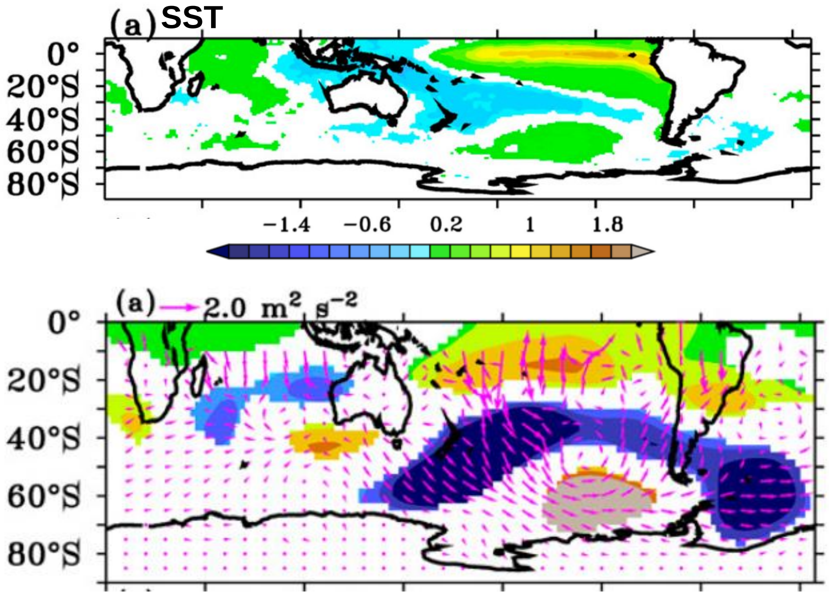


Seasonality and Passage: *Indian* Ocean

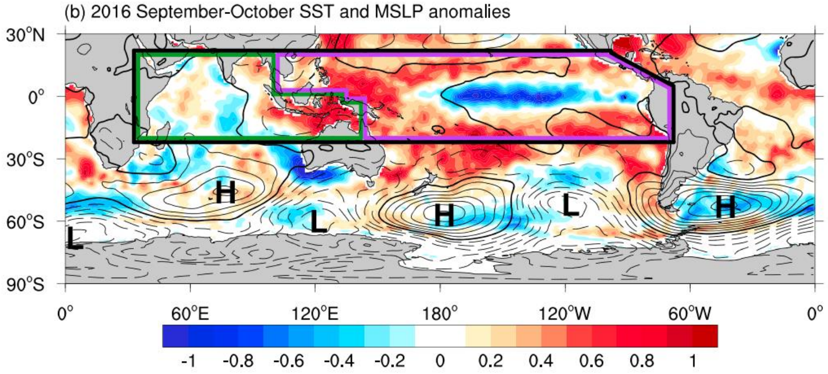


Tropical Indian Ocean act as a bridge !

Indian Ocean Impacts Antarctic: *Stationary* Wave



Nuncio and Yuan (2015)



Purich and England (2019)

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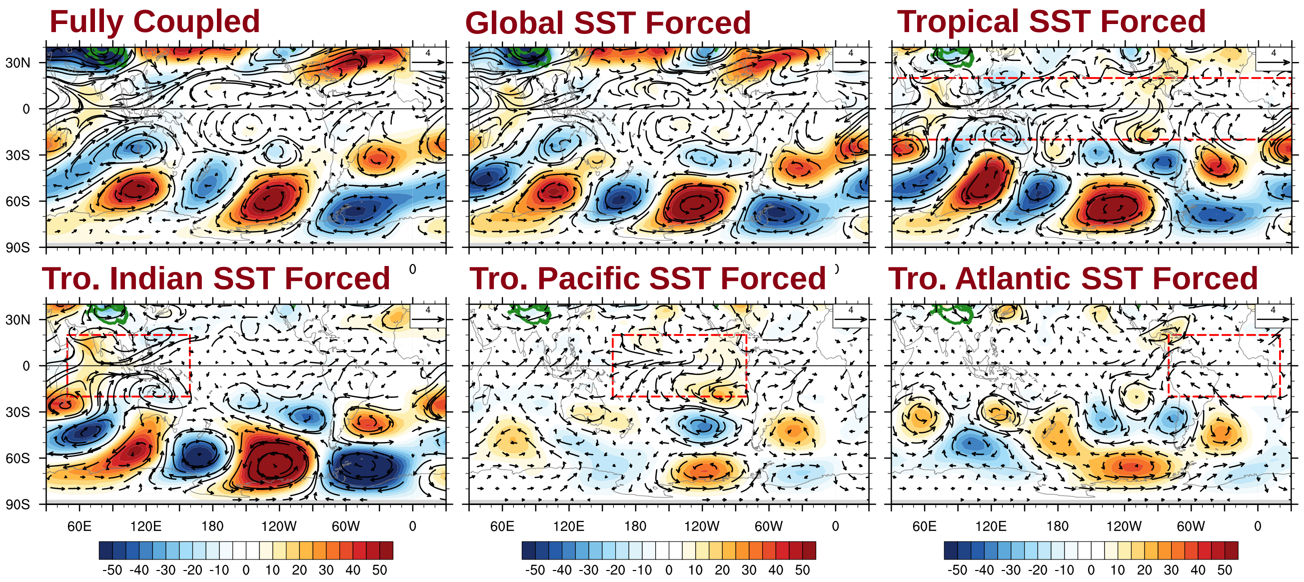
TP ➔ Antarctic: *Stationary* Wave by *Indian* Ocean

NoTibet ➔ Wind anomaly ➔ Indian Ocean SST anomaly ➔ Wave-5 pattern

Upper

Austral winter



Southward and eastward

$$\frac{C_{gx}}{C_{gy}} \sim \frac{L_y}{L_x}$$

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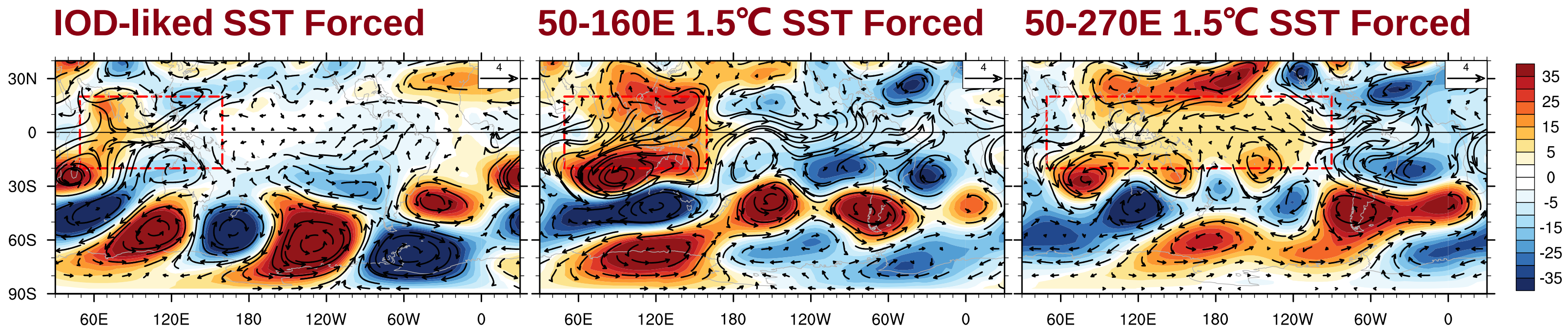
Wave *Number* Related to Forcing Size



wave number of 5

wave number of 3-4

wave number of 2-3

Size **and** ***sign*** **of the forcing determine the response wave number**

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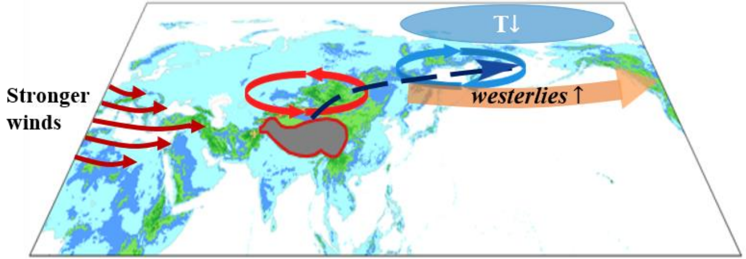
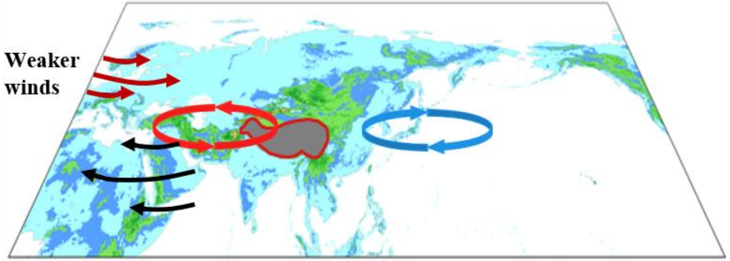
From TP to *Arctic*

Boreal winter 200hPa

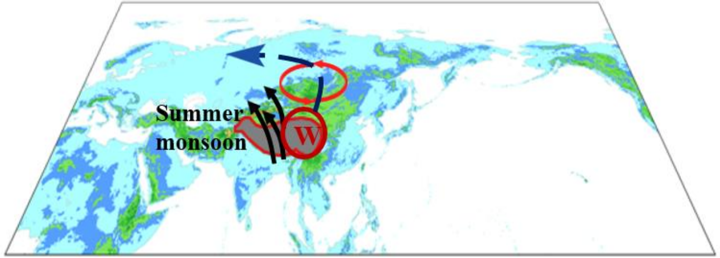


Boreal summer 200hPa



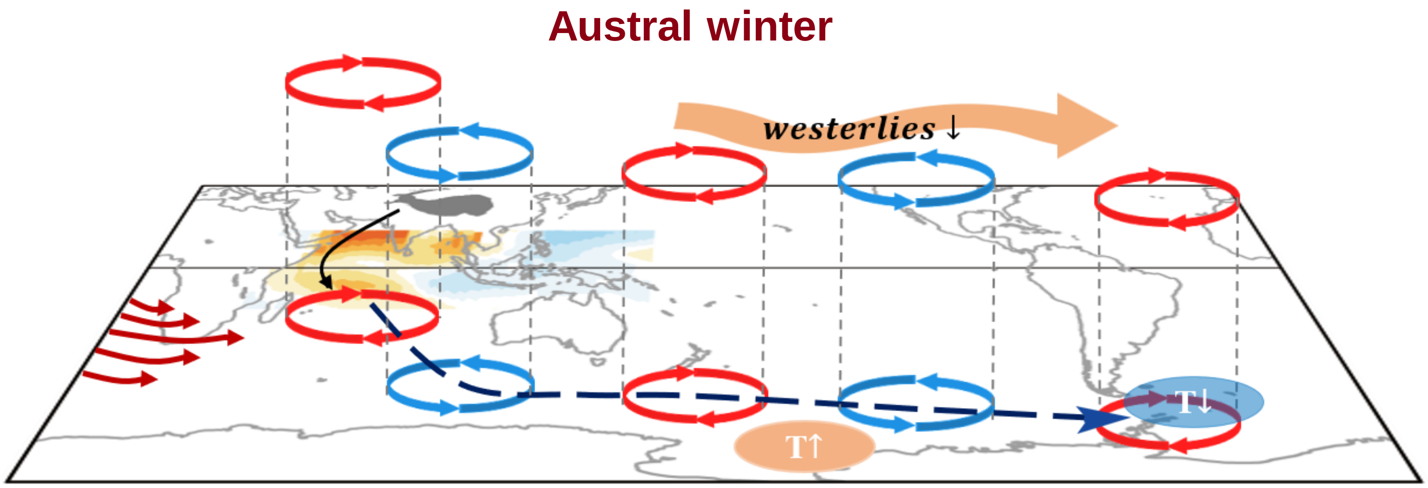
Boreal winter surface

Boreal summer surface



Directly by topography-forced stationary waves

From TP to *Antarctic*



Indirectly by *Indian Ocean* SST-forced stationary waves

Summary

- **Connection from TP to Arctic and Antarctic:** ***Robust***
- **Seasonality and Passage:** ***Winter***
- **Mechanism:** ***Forced Stationary Wave***
- **Background:** ***Planetary Winds*** **and** ***Monsoon***

LaCOAS
北京大学气候与海-气实验室

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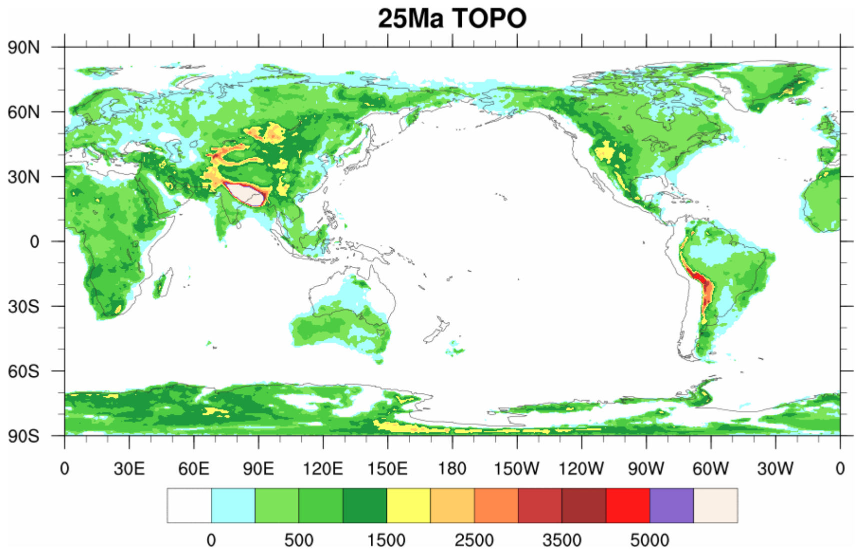
TP: *determining* the *Modern GMOC*

Tibetan Plateau → **Necessary to Modern AMOC**



Jiang R. and **H. Yang**, 2021: Tibetan Plateau: A necessary for the modern AMOC. In *Writing*.

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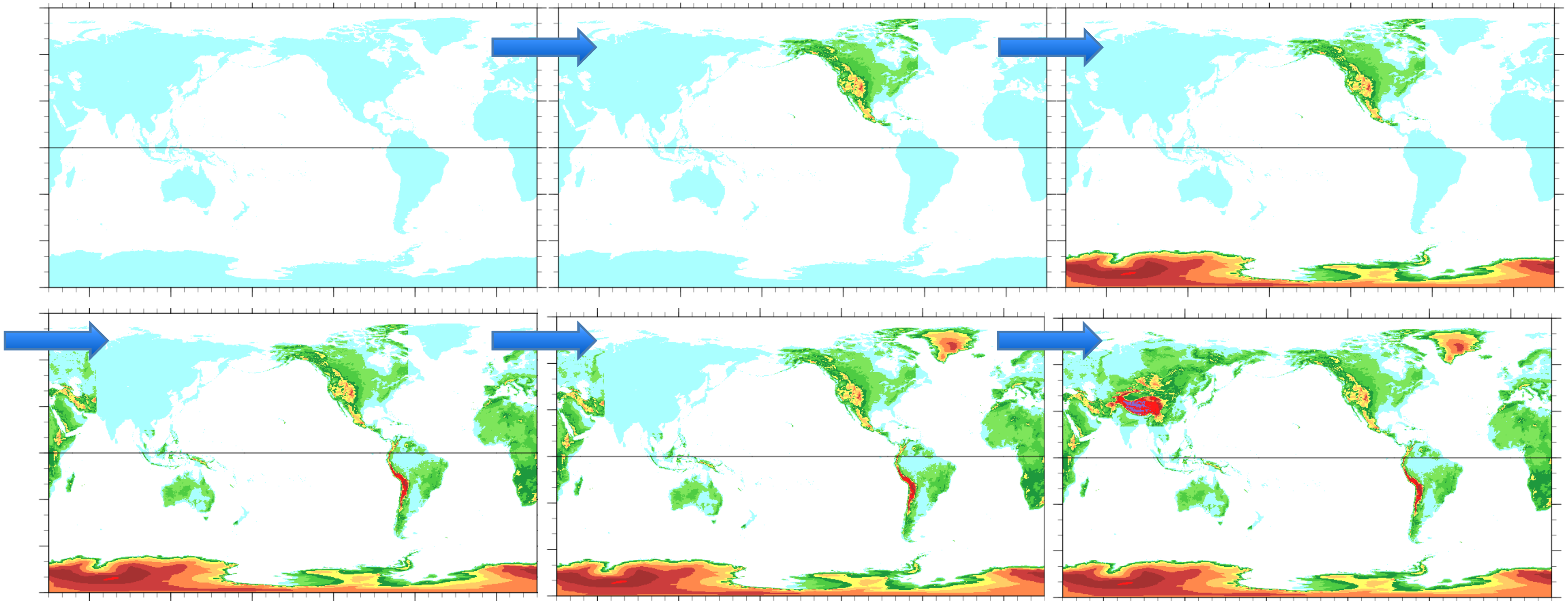
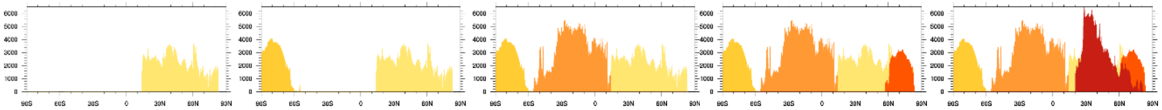
From *Flat* to *Real*

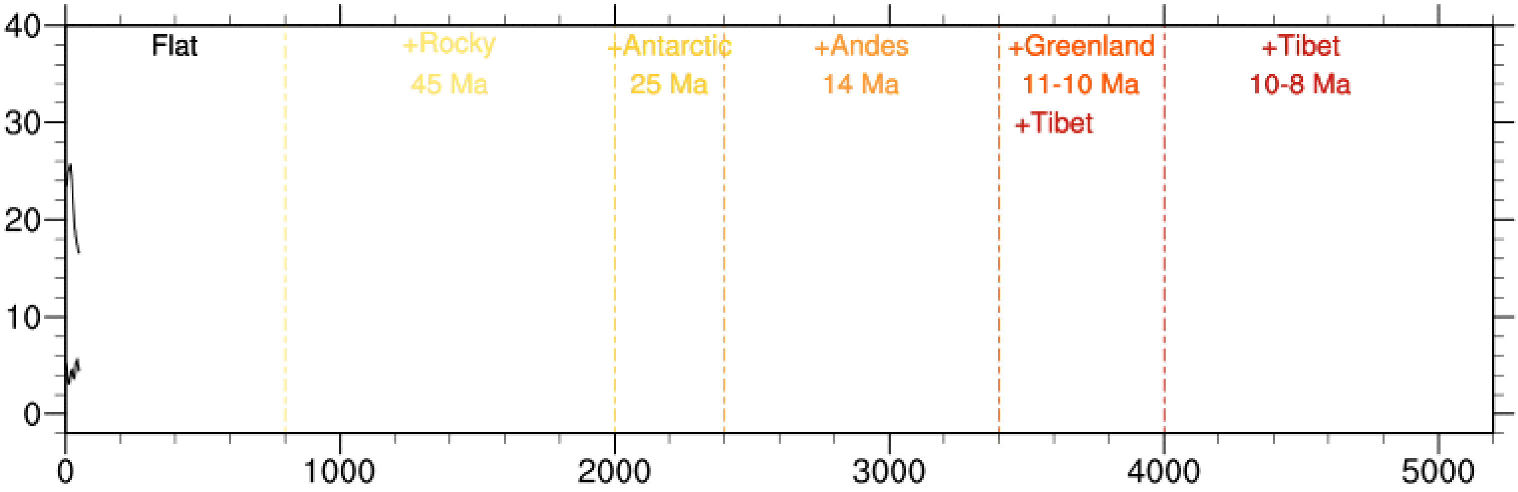
Flat | **Rocky 45Ma** | **… + Antarctic 25Ma**



… + Andes 14Ma | **… + Greenland 11Ma** | **… + Tibet 10Ma = Real**

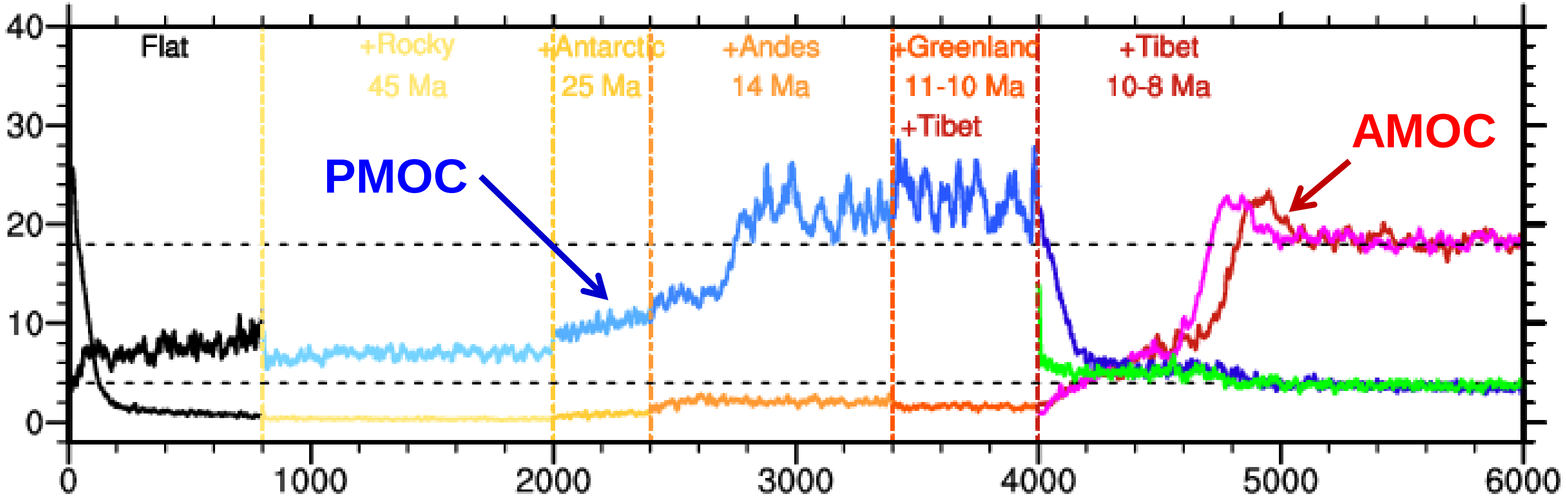
From *Flat* to *Real*

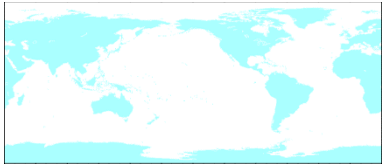


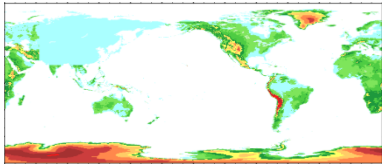


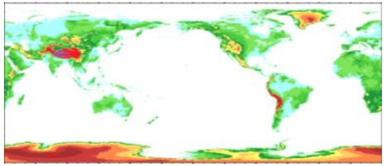
TP: *determining* the *Modern GMOC*

Total 6000 Years Simulations

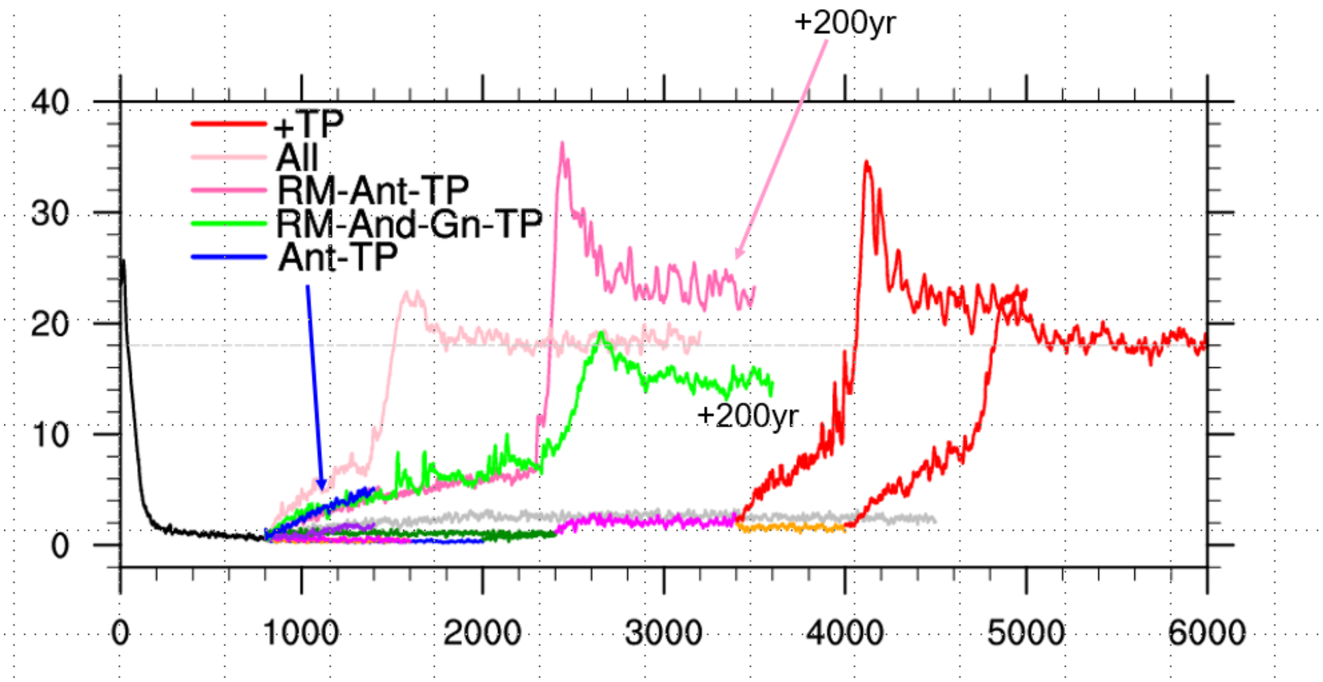








TP: *determining* the *Modern GMOC*

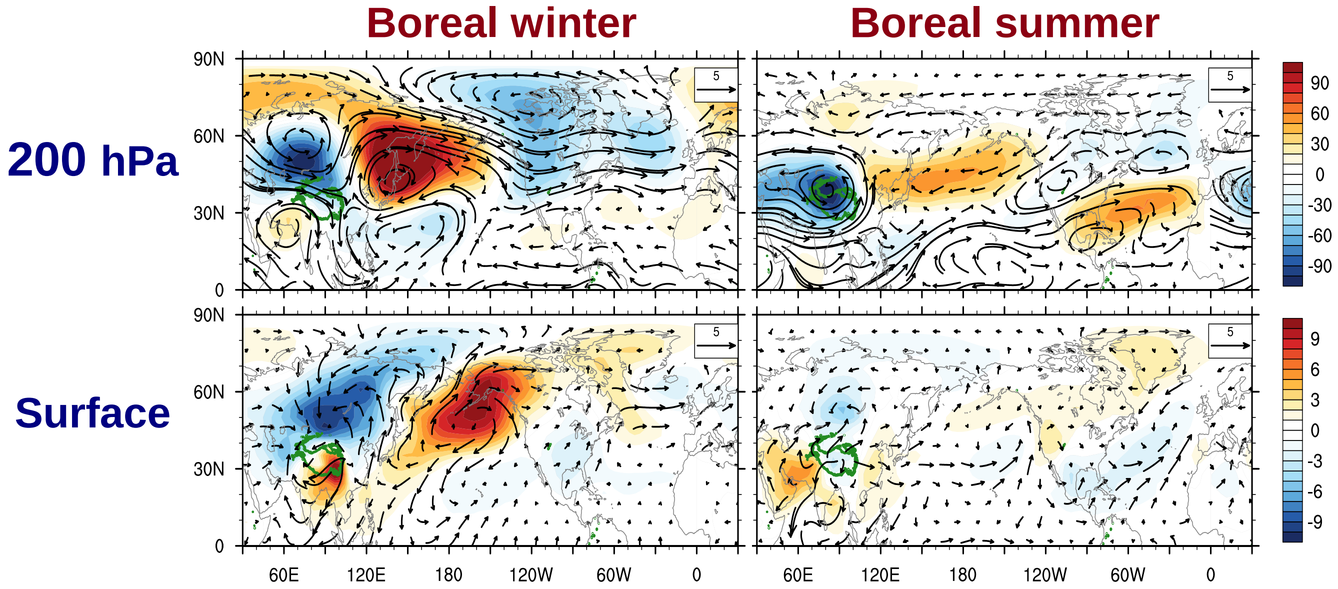


Experiments: *Topography Combination*

单个地形	试验时间	
Flat	1-1600	平板
Only _Rocky	801-2000	45Ma
Only _Ant	801-1600	25Ma
Only _Andes	801-1600	14Ma
Only _Greenland	801-1600	11-10Ma
Only _Tibet	801-4700	10-8Ma
Only _All	801-3200	全地形

组合地形试验	试验时间
Only _Tibet _Rocky	801-1400
Only_Tibet _Rocky _Ant	801-3400
Rocky-Ant	2001-2400
Rocky-Ant-Andes	2401-3400
Rocky-Ant-Andes-Green	3401-4000
Rocky-Ant-Andes-TP	3401-5000
Rocky-Ant-Andes-Gn-TP	4001-6000

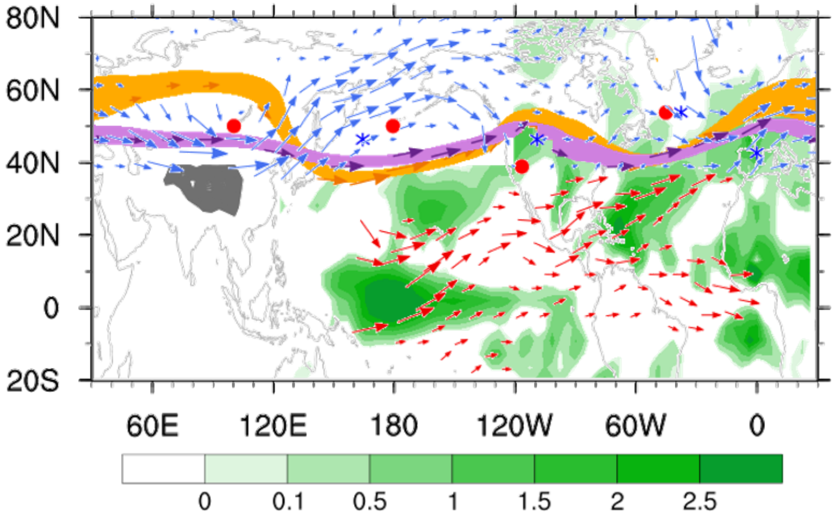
Seasonality: *Stationary Wave* Structure



TP located in winter strong westerlies

From *TP* to *AMOC: Atmosphere Dynamics*

Stationary Waves with Tibetan Plateau



NoTibet ➡ Annular mode ⇑ ➡ Westerlies ⇑ ➡ Moisture transport ⇑

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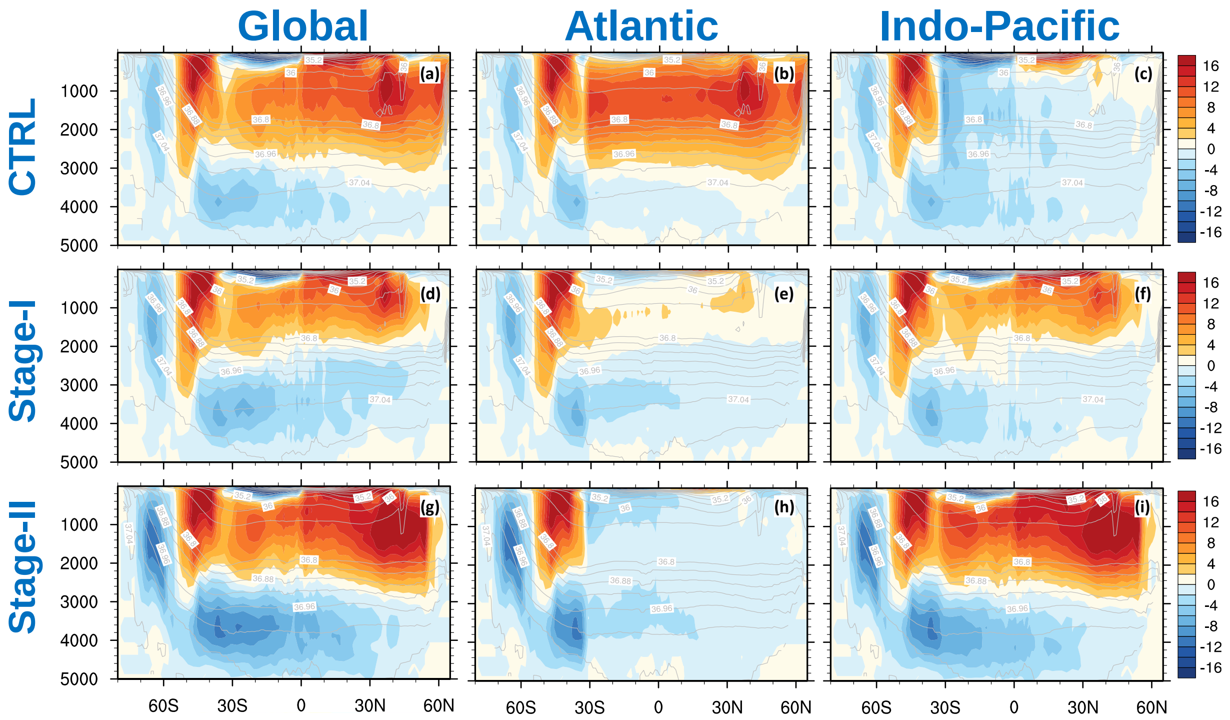
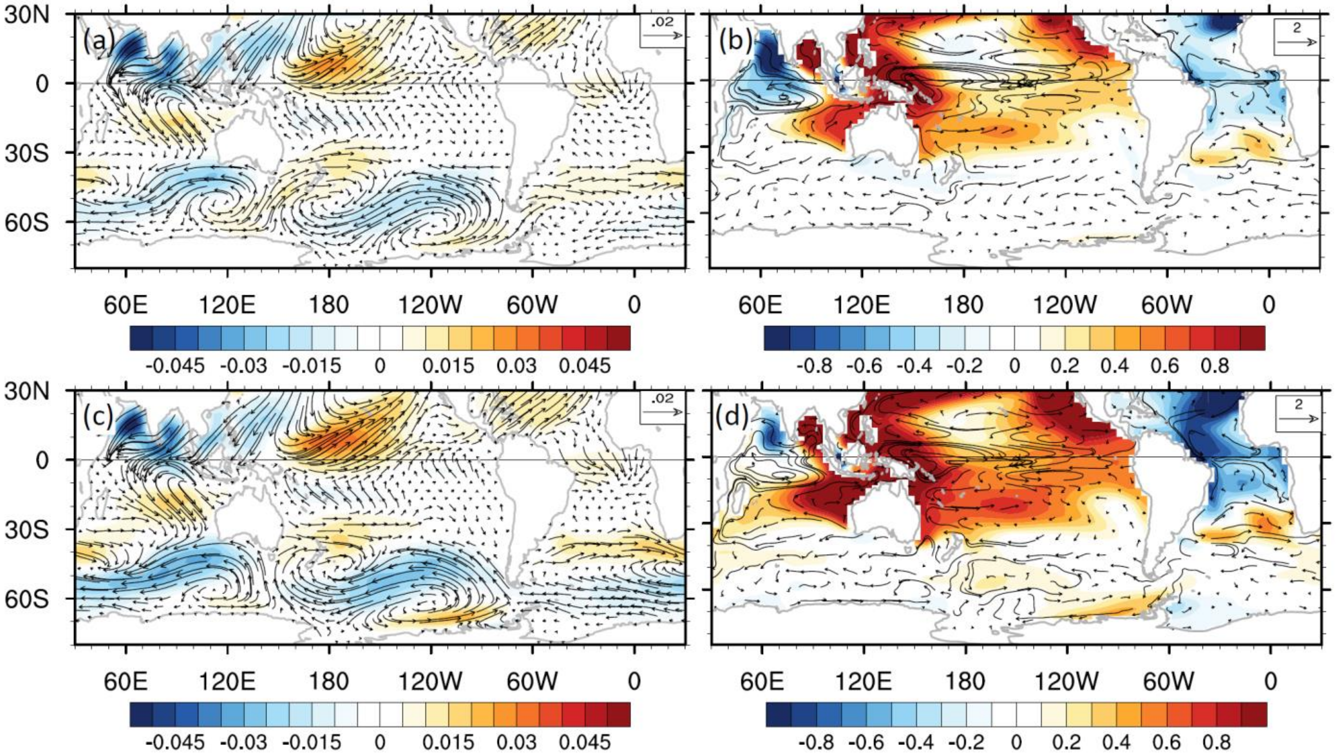
NoTibet: AABW Enhanced



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



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