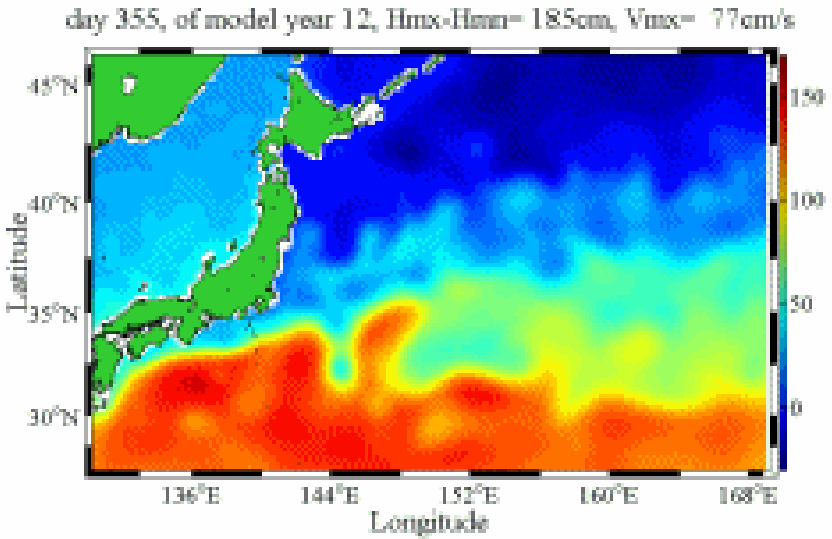
Development of a 1/16° Eddy-resolving Global Ocean Simulation within an Earth System Model Framework

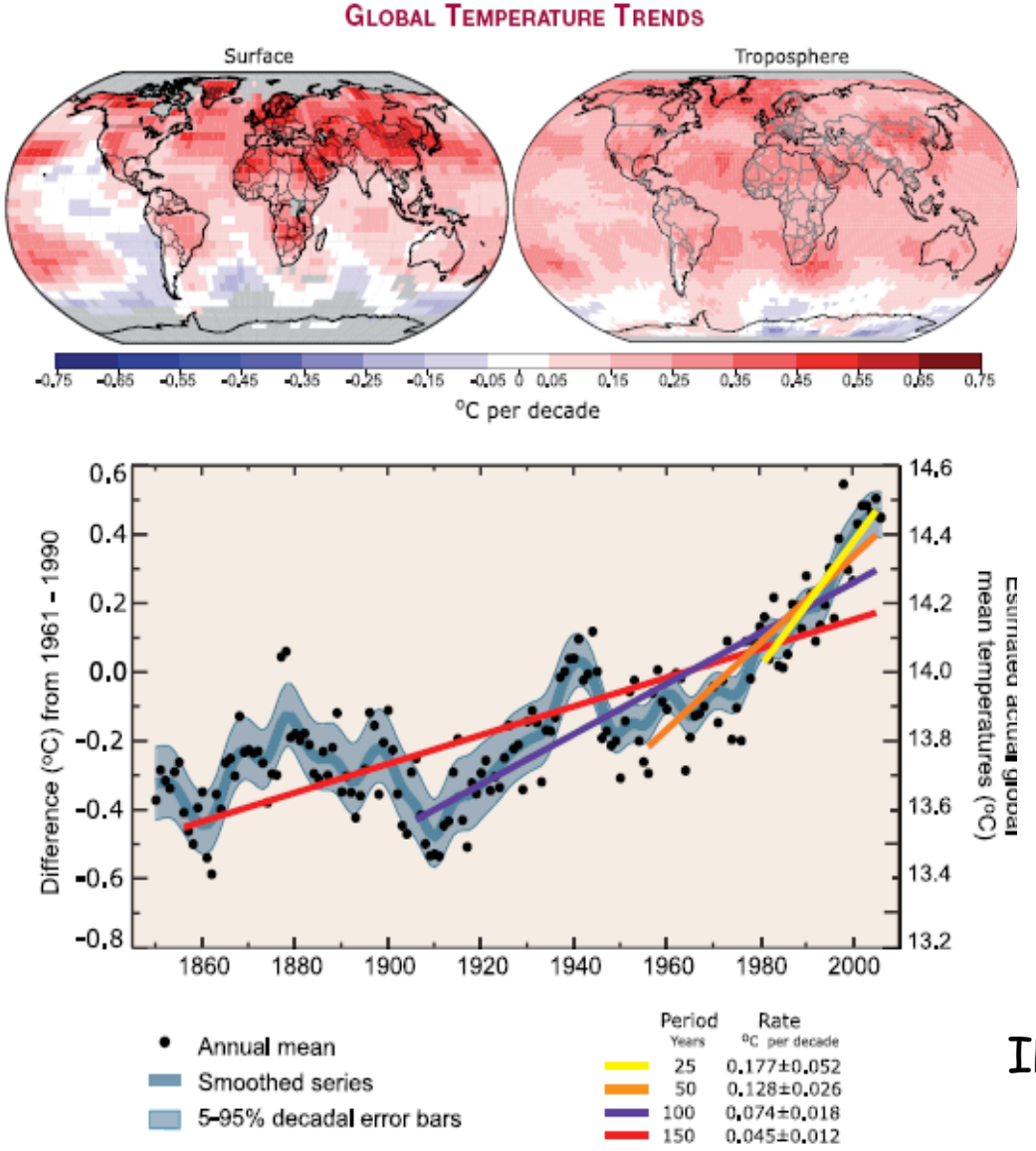


Yu-Heng Tseng, Chih-Chieh Young, Wen-ien Yu, Mu-hua Chien, Yu-Chiao Liang

High-performance Computing & Environmental Fluid Dynamics Laboratory (HC/EFDL)
Department of Atmospheric Sciences
National Taiwan University
http://efdl.as.ntu.edu.tw

Acknowledgement: computing resources from NCHC, Taiwan and NERSC, US

Climate change and ocean



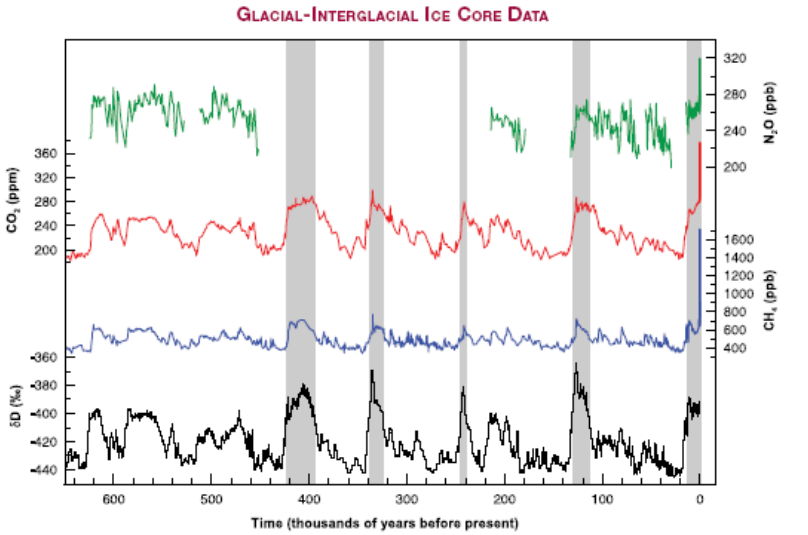
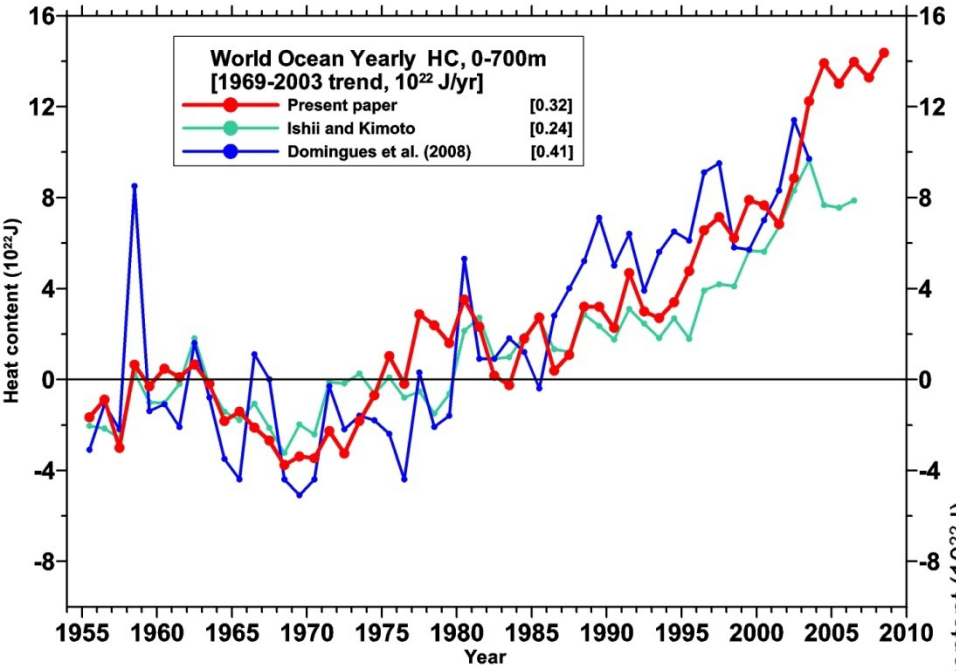
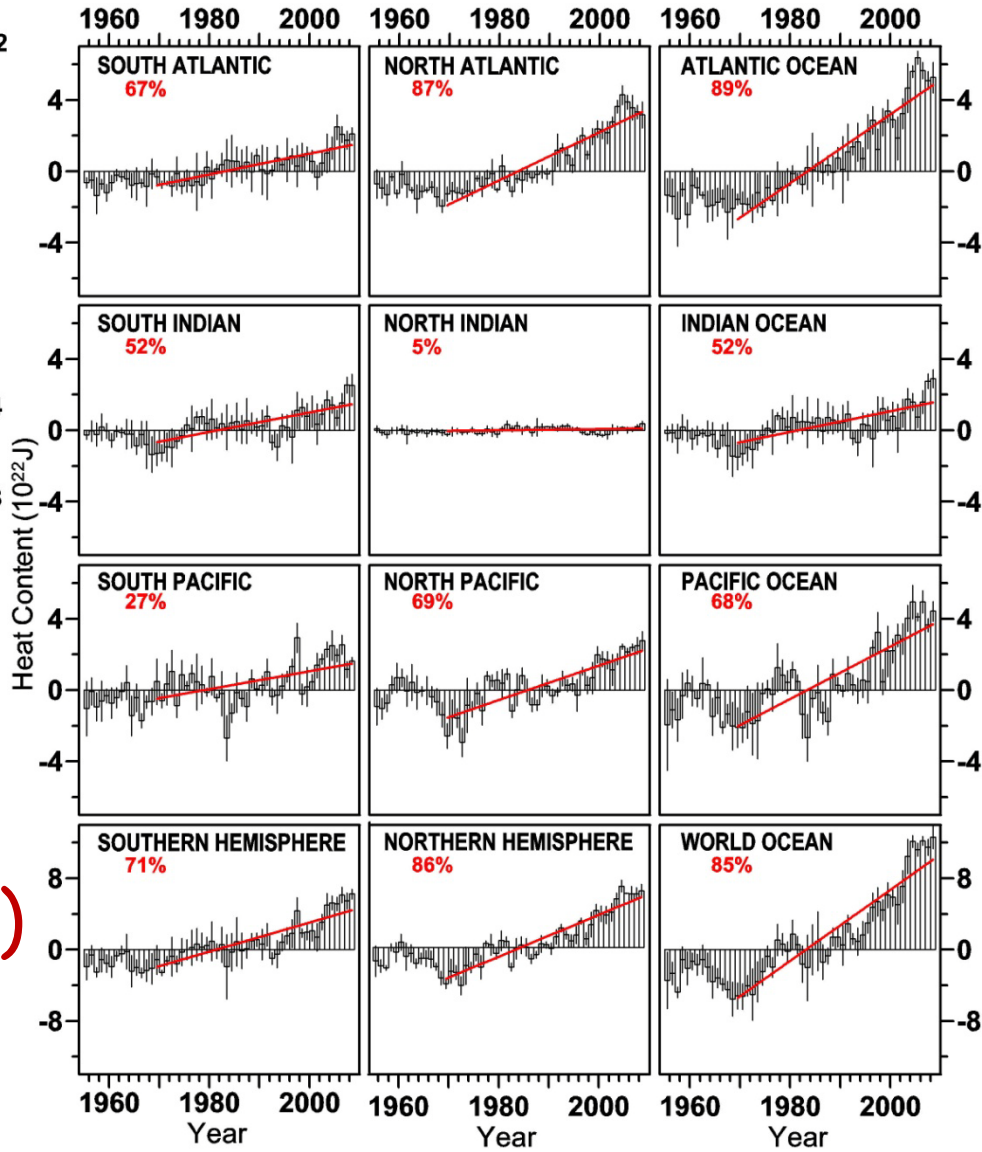


Figure TS.1. *Variations of deuterium (δD) in antarctic ice, which is a proxy for local temperature, and the atmospheric concentrations the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in air trapped within the ice cores and from rece atmospheric measurements. Data cover 650,000 years and the shaded bands indicate current and previous interglacial warm period {Adapted from Figure 6.3}*

IPCC AR4 WG1 Technical Summary





Global ocean variation (long term warming trend)

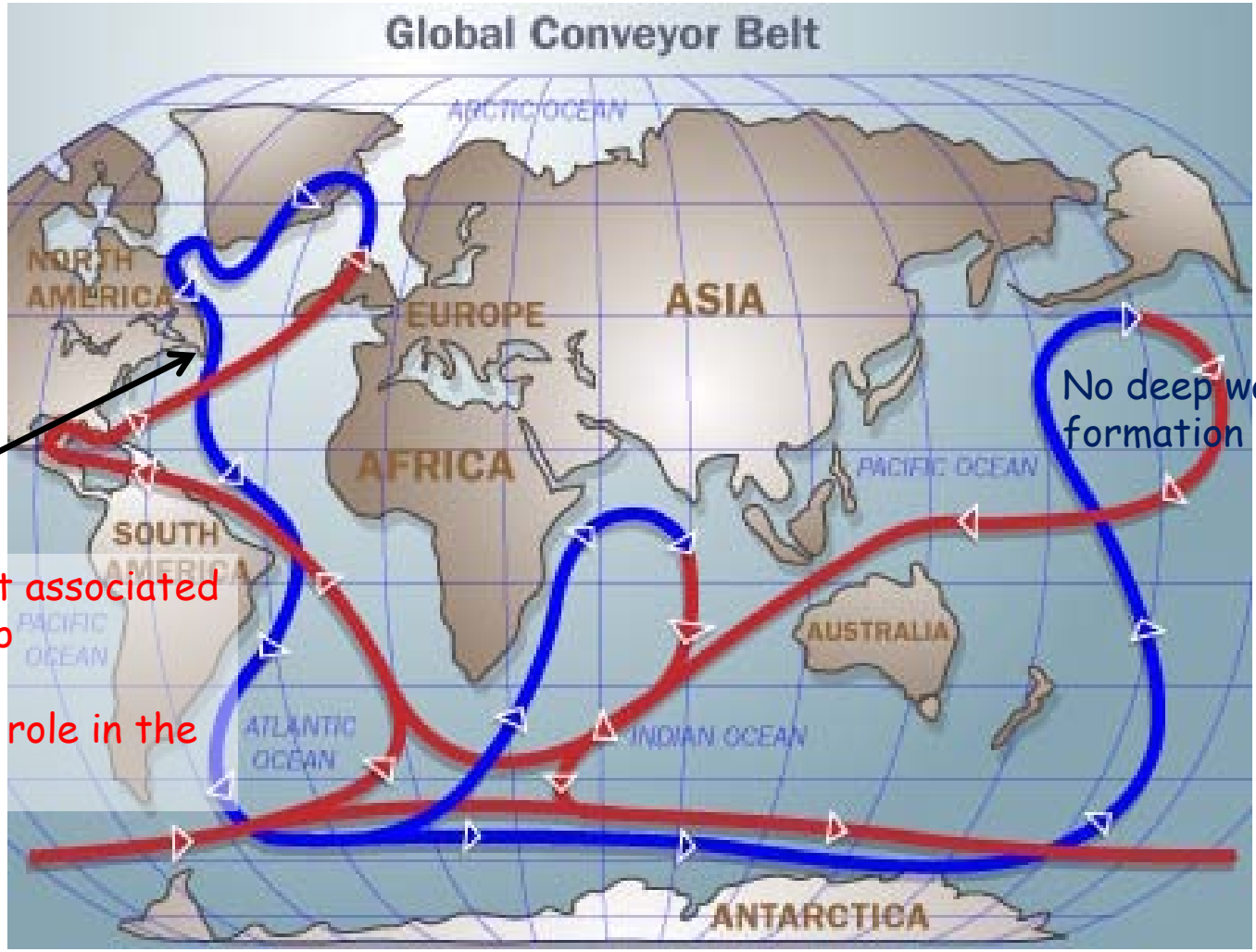
Levitus et al. (2009)

Global Thermohaline Circulation:

1, thermal forcing, when water is cooled and sinks, and

2, haline forcing, when excess precipitation makes water less dense, and thus resistant to sinking.

Driven by the sinking of cold, saline water



No deep water formation

The heat transport associated with "Atlantic deep circulation" plays an important role in the present climate.

http://science.howstuffworks.com/ocean-current3.htm

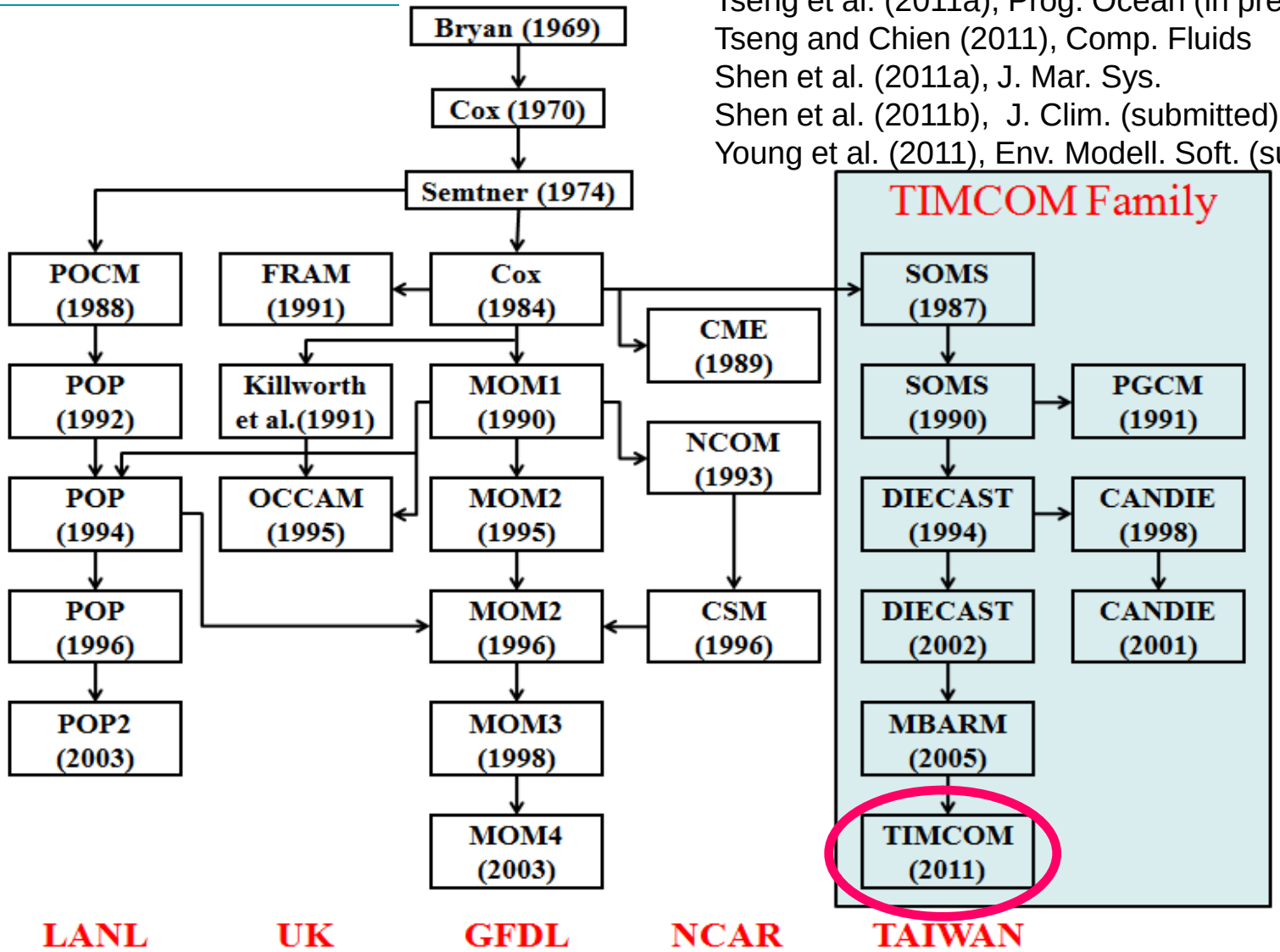
Objectives

- Building and redesigning a high-resolution global ocean circulation model for global ocean climate study in an Earth System Model Framework
- Resolving multi-scale dynamics with the most efficient two-way coupling approach (serial code) or parallel solver (parallel code) in high accuracy
- Studying the Pacific ocean climate
- Investigating the regional circulation in the vicinity of Taiwan

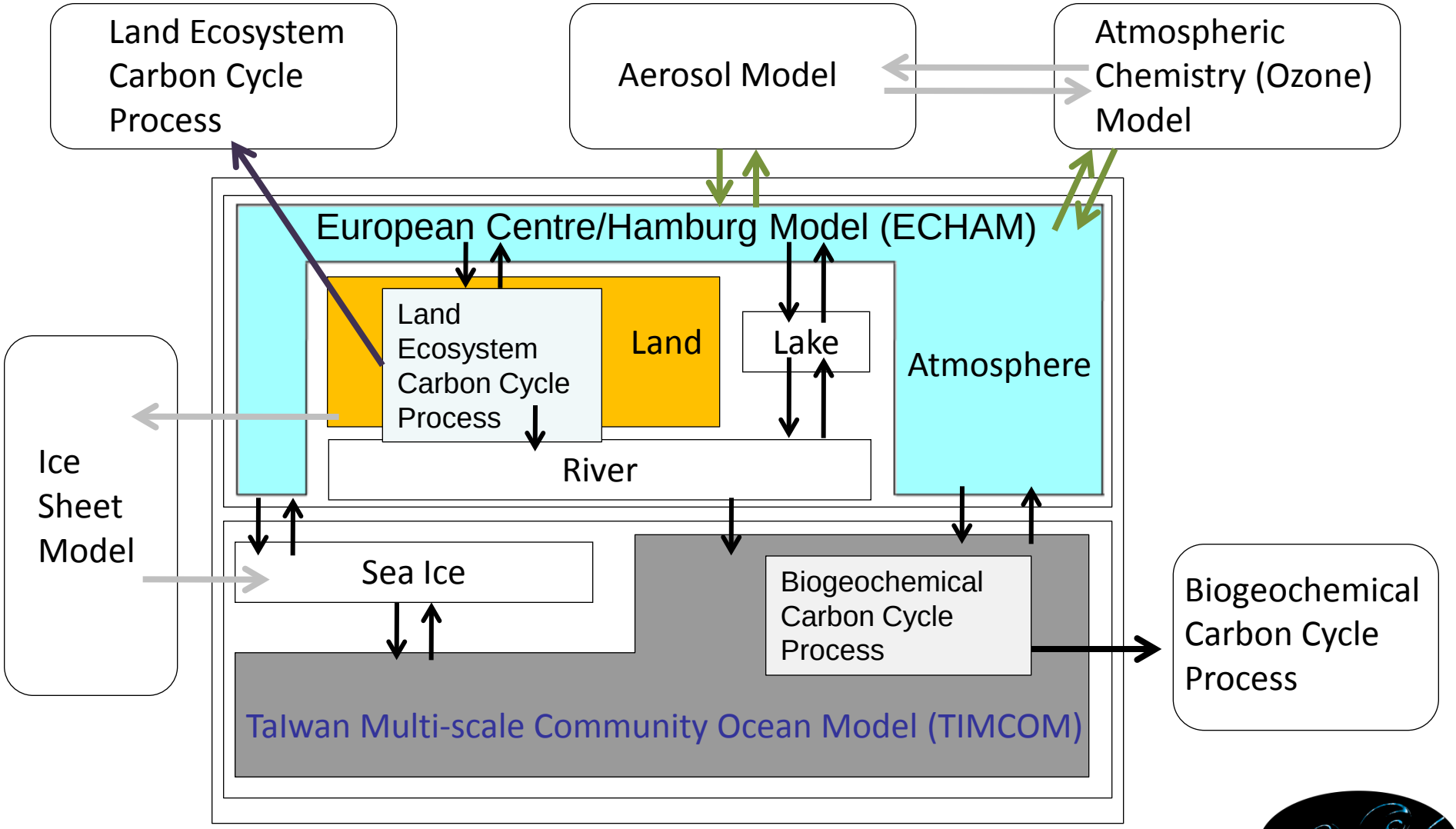
Parallel Domain-Decomposed Taiwan Multi-Scale Community Model (PD-TIMCOM)

http://efdl.as.ntu.edu.tw/research/timcom

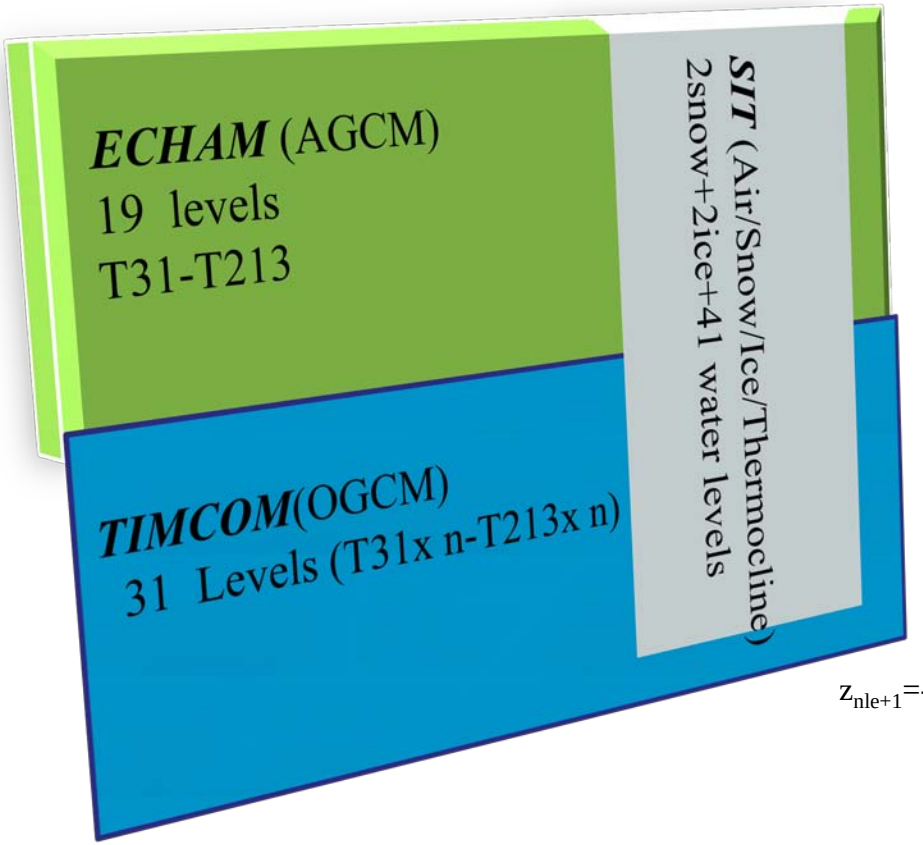
Tseng et al. (2011a), Prog. Ocean (in press)
Tseng and Chien (2011), Comp. Fluids
Shen et al. (2011a), J. Mar. Sys.
Shen et al. (2011b), J. Clim. (submitted)
Young et al. (2011), Env. Modell. Soft. (submitted)

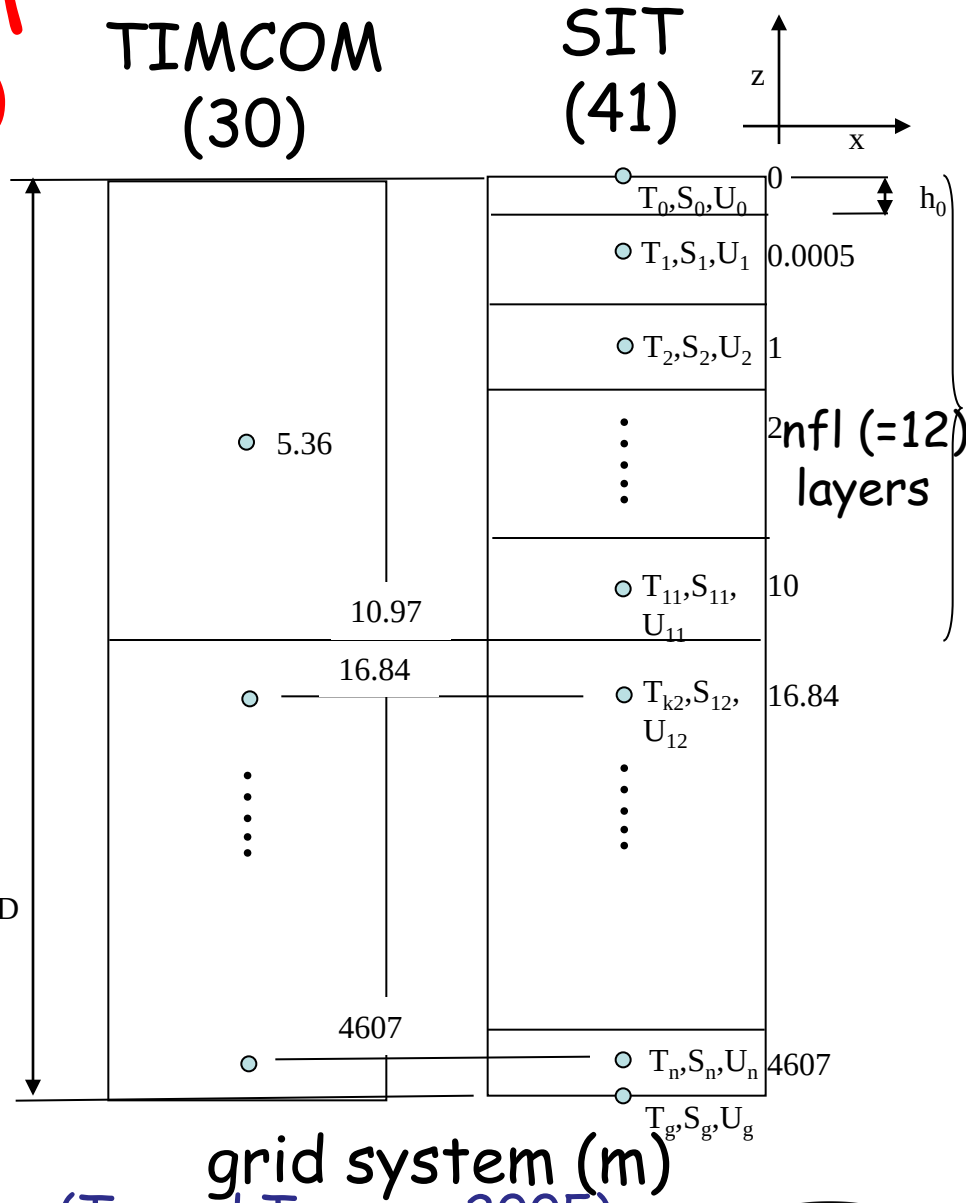


ECHAM/Taiwan Earth System Model



ECHAM/TWESM
(ECHAM5/SIT/TIMCOM)

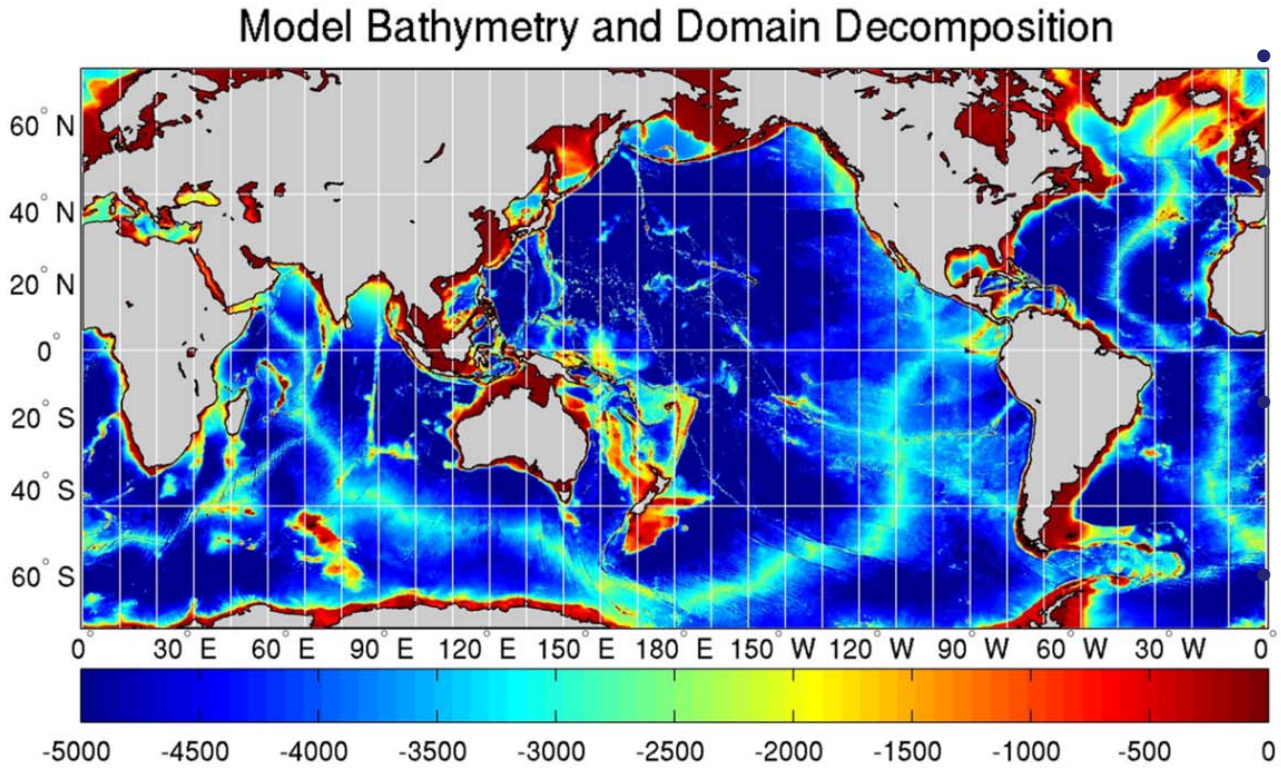




- Improved MJO
- Better diurnal cycle
- Improved cool-skin simulation (Tu and Tsuang, 2005)

Tseng and Chien (2011)

Parallel Domain-Decomposed Taiwan Multi-Scale Community Model (PD-TIMCOM)



- Bathymetry from 1-min Etopo1
- Pacanowski and Philander Vertical mixing (1982) and Smagorinsky horizontal mixing (1993).
- Initial Temperature and Salinity from NOAA WOA 09.
- Surface wind forcing from Hellerman and Rosenstein (1983)

- 1/16°and 1/4° horizontal resolution, latitudes covers from 72°S to 72°N. with 51 linear exponential levels vertically. (1440x792x51)
- Primitive, hydrostatic equation
- Fourth-order numerics combined Arakawa A and C-grid (1977)
- Rid-lid approx. and Free surface are used (Yang et al., in preparation)

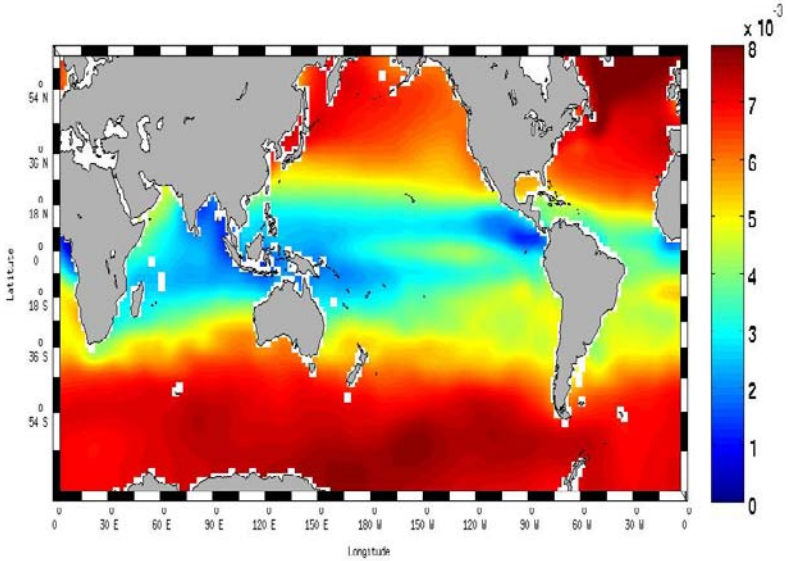
EQUATION OF STATE

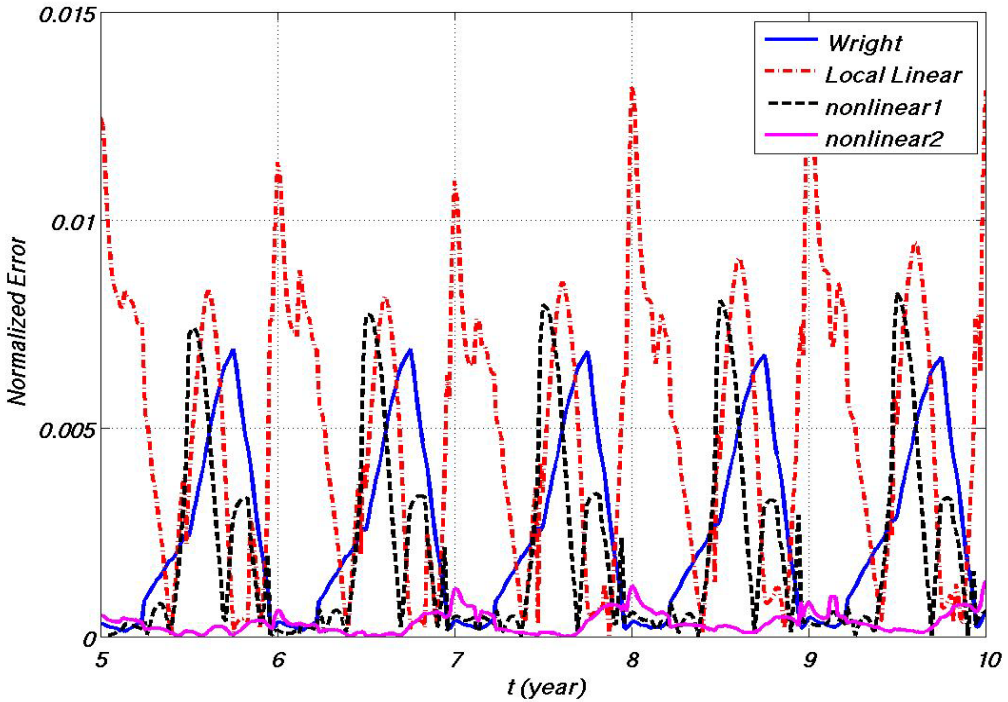
Wright's: $(\alpha - \alpha_0)(p + p_0) = \lambda \Rightarrow \rho = \dfrac{p + p_0}{\lambda + \alpha_0 (p + p_0)}$

Polynomial fit:

$$D(t, s, p) = C_0 + (C_t + C_{tt} t + C_{ts} s) t + C_s s$$

[Sanderson et al., 2001]





- *UNESCO*: standard solution.
- Error is normalized.
- Largest error of *Wright's* in autumn.
- Largest error of *Local Linear* in winter.
- Largest error of *nonlinear1* in summer.
- Largest error of *nonlinear2* in winter.

RAW-FILTER

- 3rd-order accuracy in Amp.
- reduce time-splitting instability.
- easy to implement.
- low computational cost.

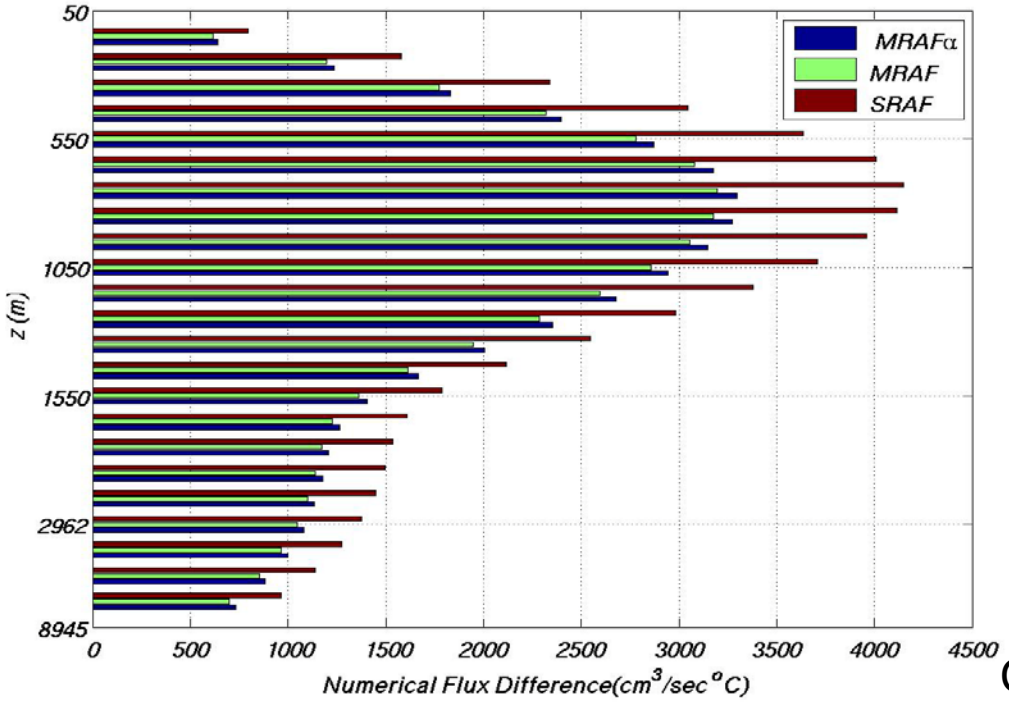
Young et al. (in prep.)

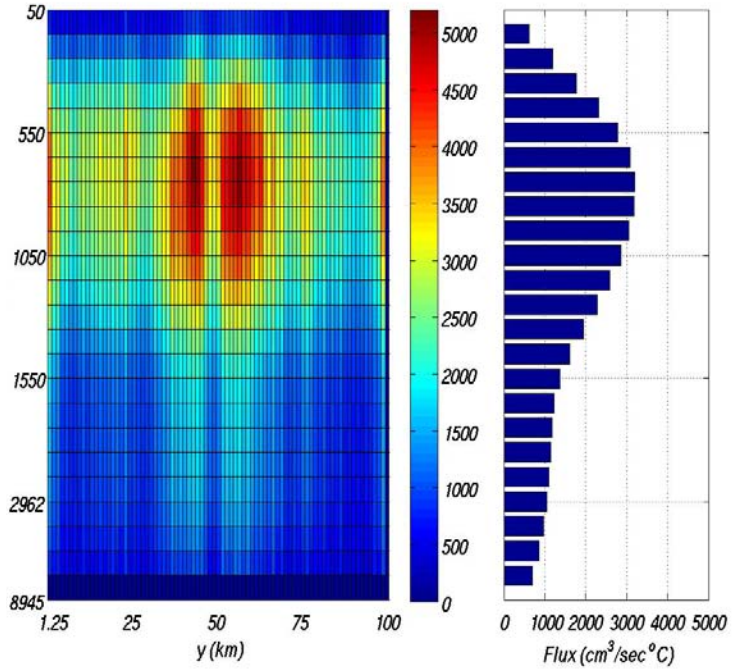
$$\overline{\overline{F}}(t) = \overline{F}(t) + \frac{\nu\alpha}{2}\left[\overline{\overline{F}}(t-\Delta t) - 2\overline{F}(t) + F(t+\Delta t)\right]$$

$$\overline{F}(t+\Delta t) = F(t+\Delta t) - \frac{\nu(1-\alpha)}{2}\left[\overline{\overline{F}}(t-\Delta t) - 2\overline{F}(t) + F(t+\Delta t)\right]$$

- $0.05 < \nu < 0.2$
- $\alpha = 0.53$
- ν = 0 -> *Leap-frog*
- α = 1 -> *RA-Filter*

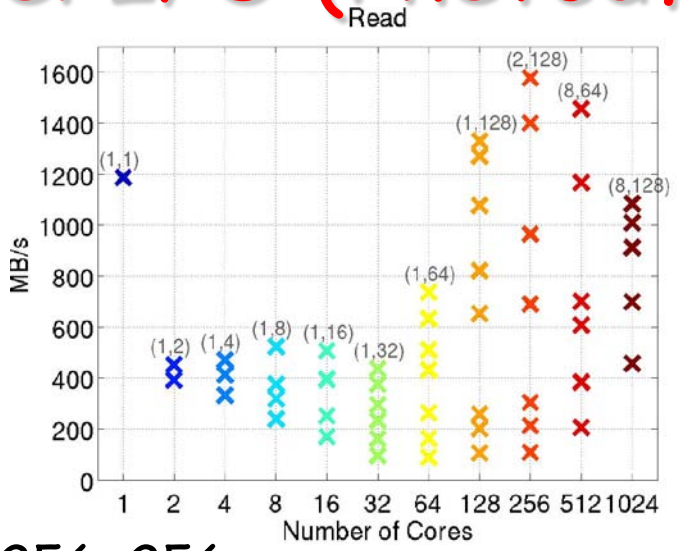
[Williams, 2009]

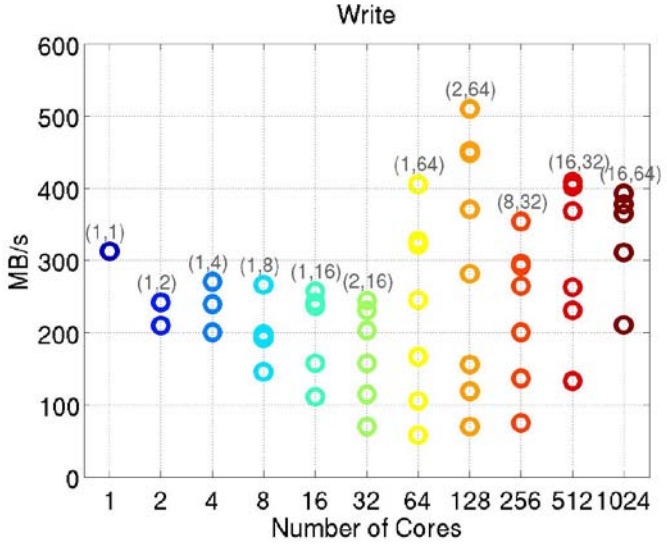




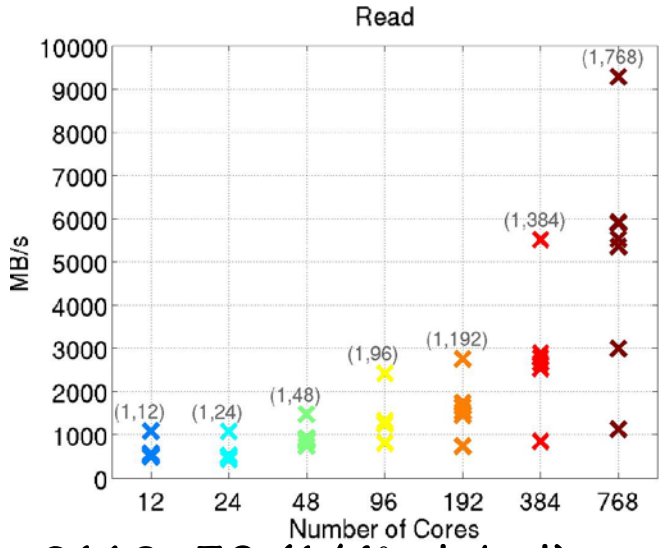
Coastal trapping Kevin wave

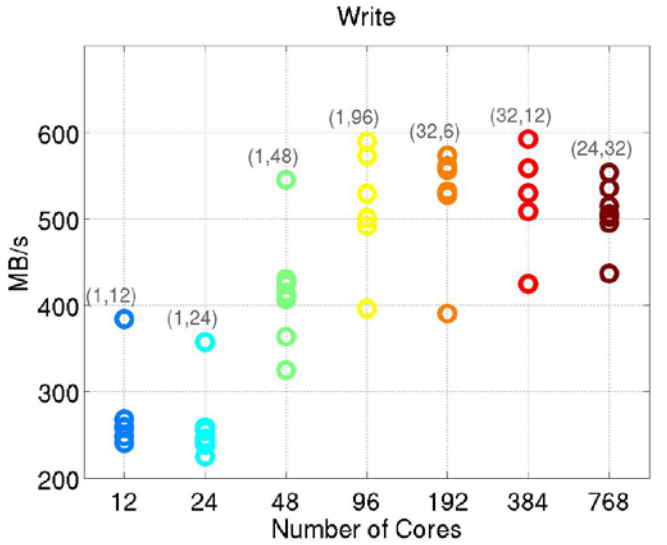
Parallel I/O (Pnetcdf)



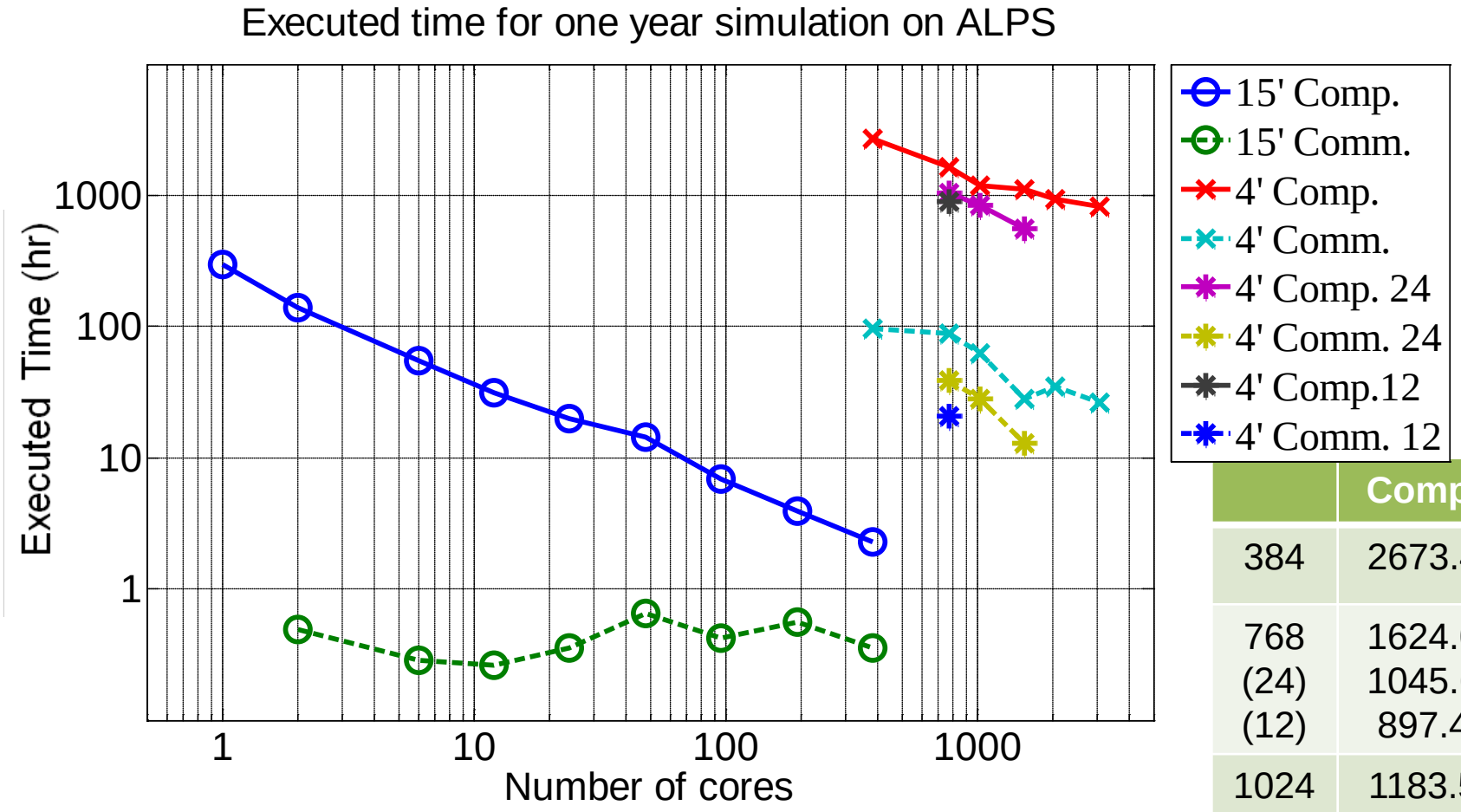


Size: 256x256x256





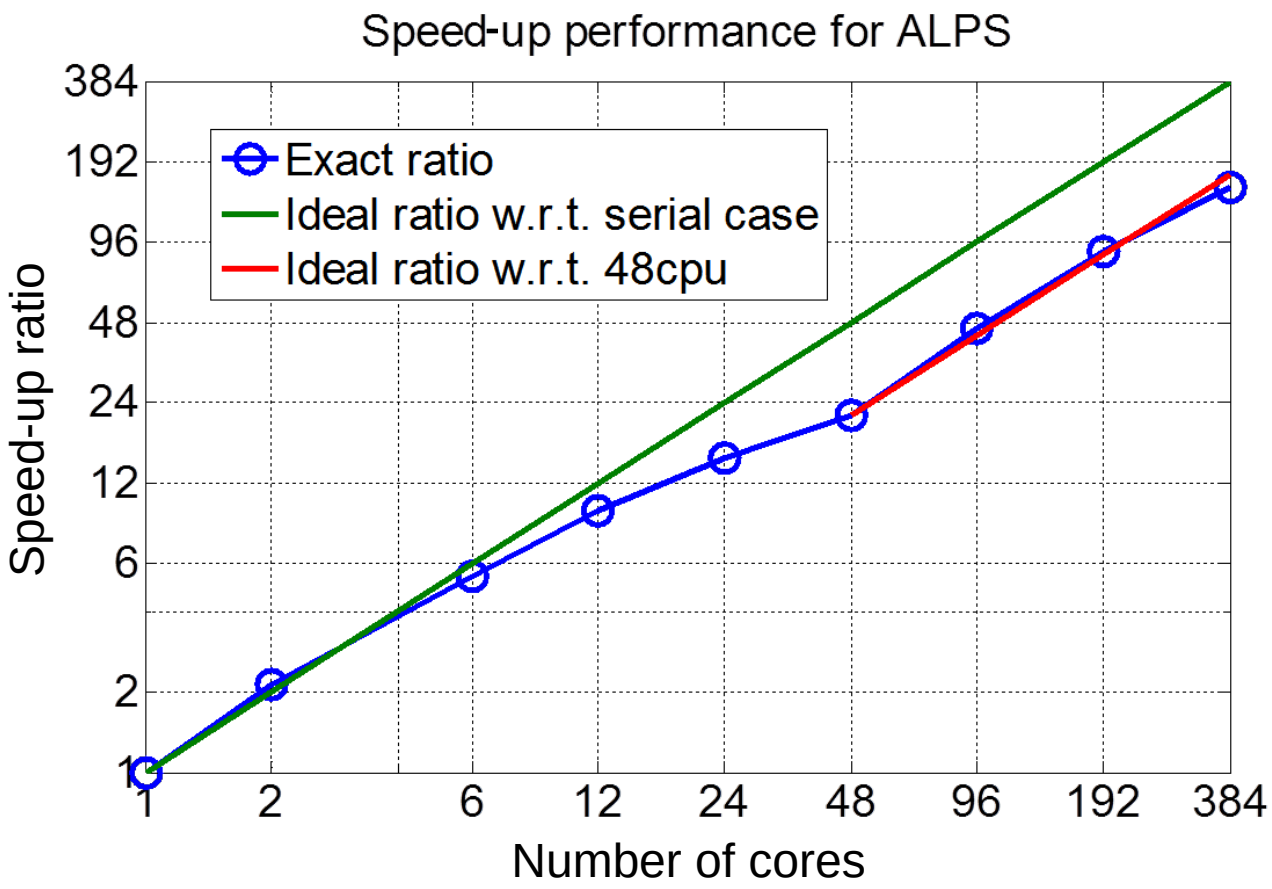
Size: 5760x3168x50 (1/4° global)



	1	2	6	12	24	48	96	192	384
Comp.	295.83	139.03	55.11	31.34	20.05	14.41	6.88	3.91	2.27
Comm.	0	0.49	0.29	0.26	0.35	0.65	0.42	0.55	0.36

	Comp.	Comm.
384	2673.4	95.9
768 (24) (12)	1624.0 1045.6 897.4	87.7 38.7 26.0
1024 (24)	1183.5 843.8	62.7 28.2
1536 (24)	1109.5 558.3	28.3 13.0
2048	941.9	34.8
3072	829.6	26.1

Speed-up Ratio



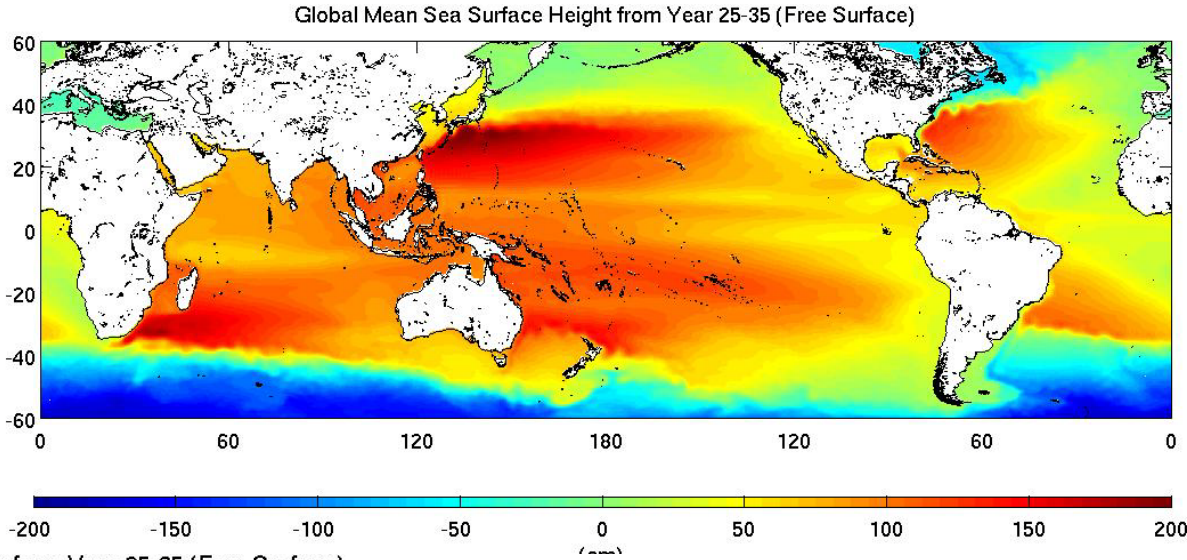
Ideal Ratio	1	Ideal Ratio	48
2	2.13		
6	5.40		
12	9.5		
24	15.0		
48	21.5	1	1
96	45.8	2	2.13
192	88.2	4	4.01
384	154	8	7.17

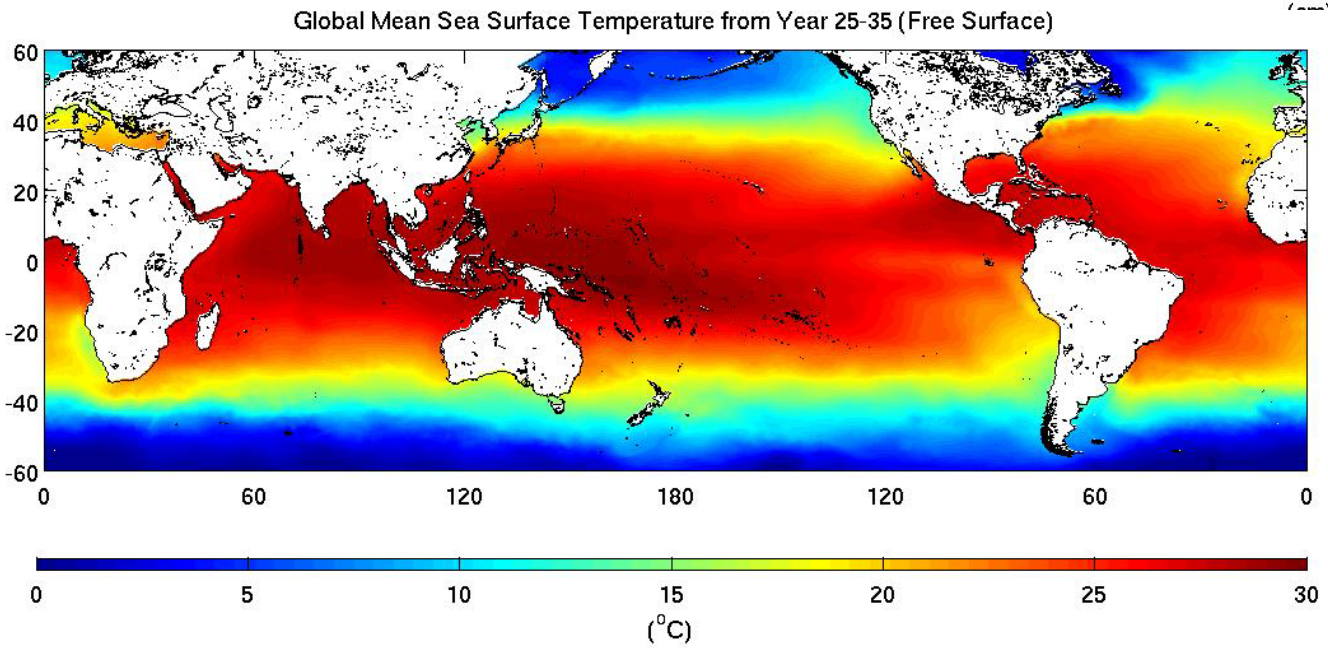
Numerical Experiments

1. 50 years TIMCOM 1/4° global simulation with Levitus (1994) and HR (1984) wind forcing (Done).
2. 50 years TIMCOM 1/4° global simulation with WOA09 and Scatterometer Climatology of Ocean Winds (SCOW, 2008) wind forcing (in proc.).
3. 2004-2010 TIMCOM 1/4° global hindcast with NOGAPS daily forcing (in prep.).
4. 1960-2010 TIMCOM 1/4° global hindcast with ECMWF monthly forcing (in prep.).

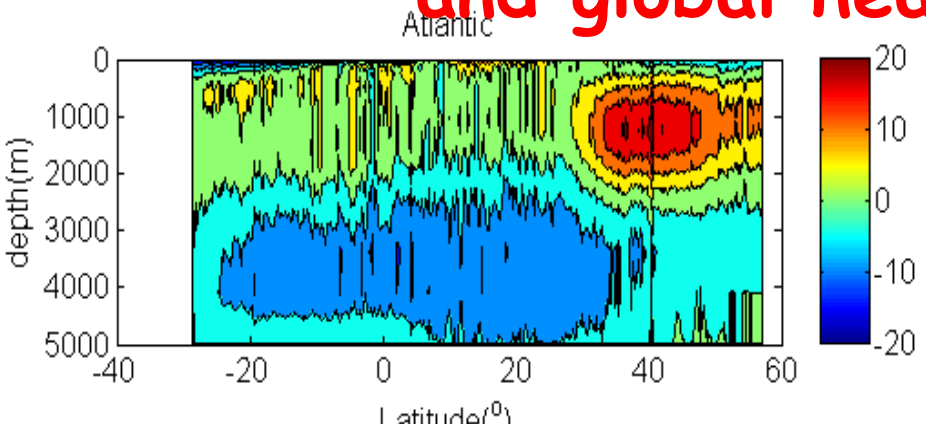
5. 30 years TIMCOM 1/16° global simulation with Levitus (1994) and HR (1984) wind forcing (in proc.).
6. 30 years TIMCOM 1/16° degree global simulation with WOA09 and Scatterometer Climatology of Ocean Winds (SCOW, 2008) wind forcing (in prep.).
7. 2004-2010 TIMCOM 1/16° degree global hindcast with NOGAPS daily forcing (in prep.).
8. 1960-2010 TIMCOM 1/16° degree global hindcast with ECMWF monthly forcing (in prep.).

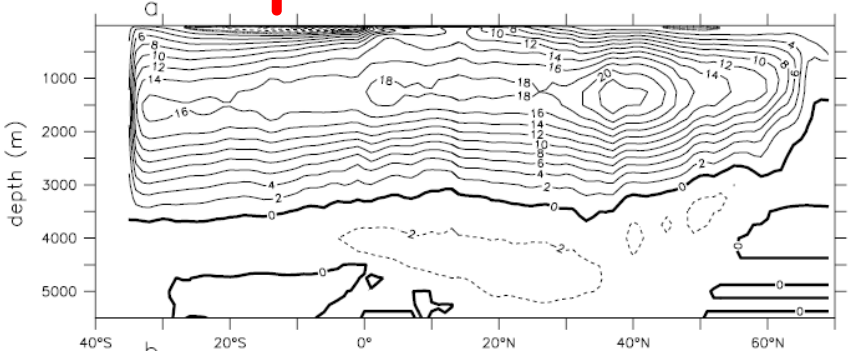
Mean SSH and SST

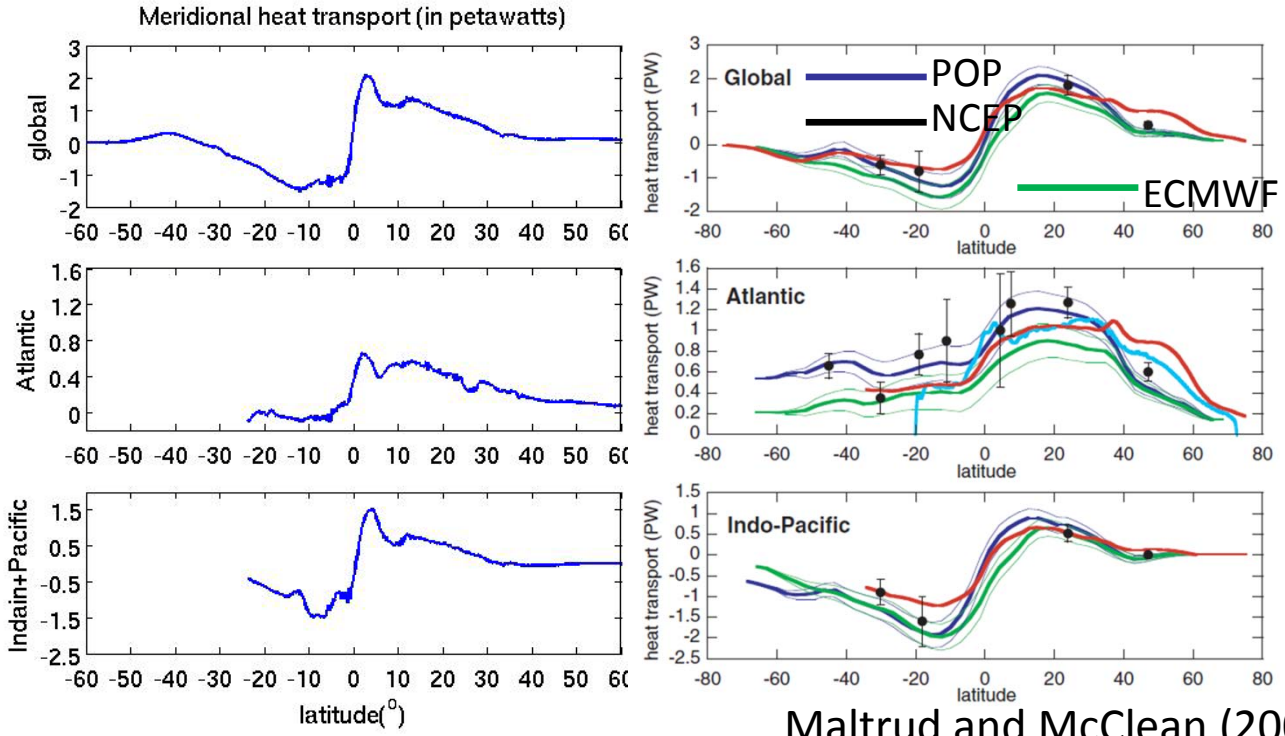




Meridional overturning streamfunction (MOC) and global heat transport



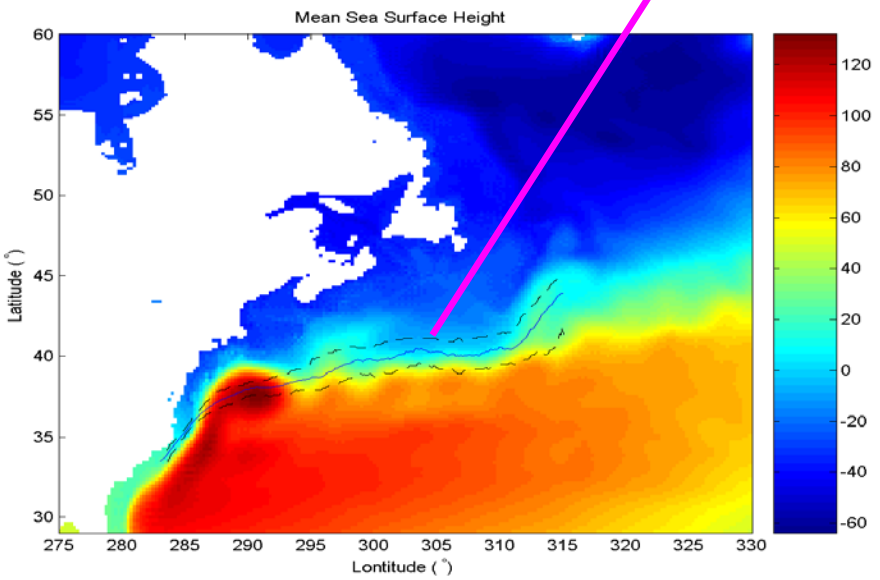


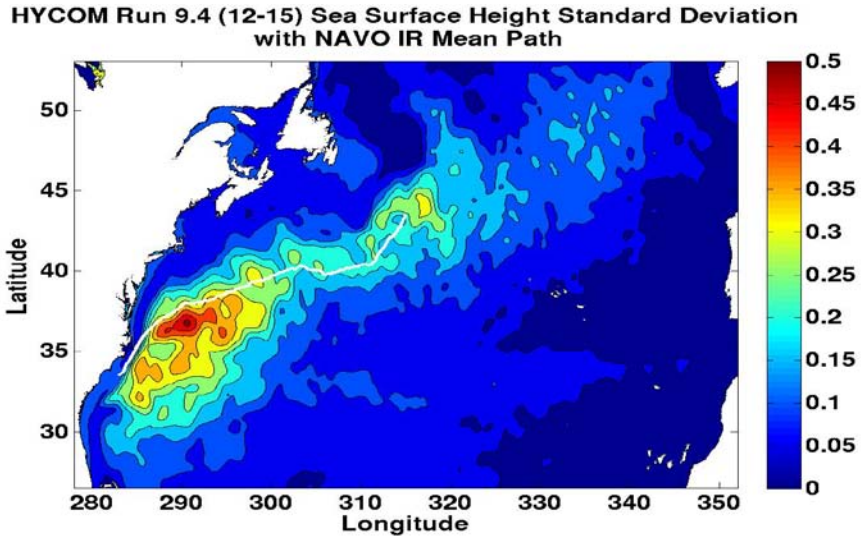


Maltrud and McClean (2005)

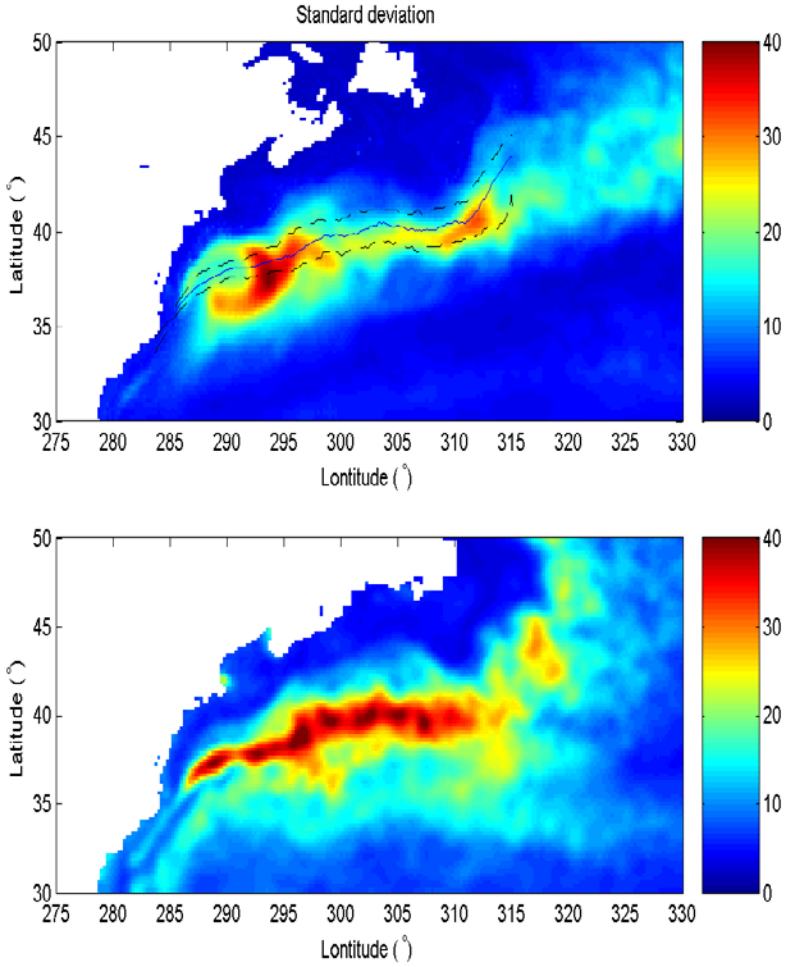
Gulf Stream

The mean Gulf Stream IR northwall pathway ±1σ (standard deviation) by Cornillon and Sirkes





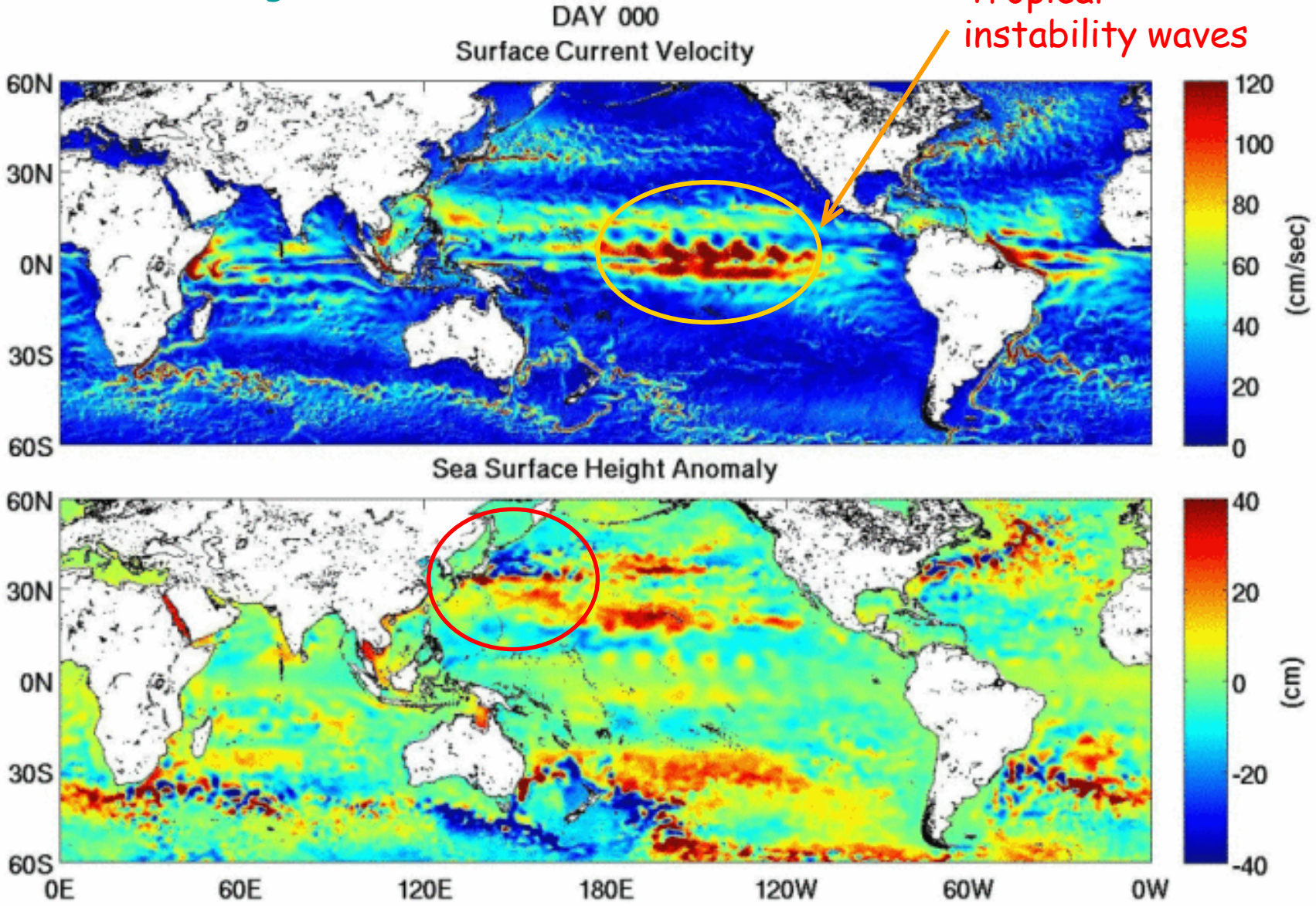
Courtesy of Jim Richman (NRL)



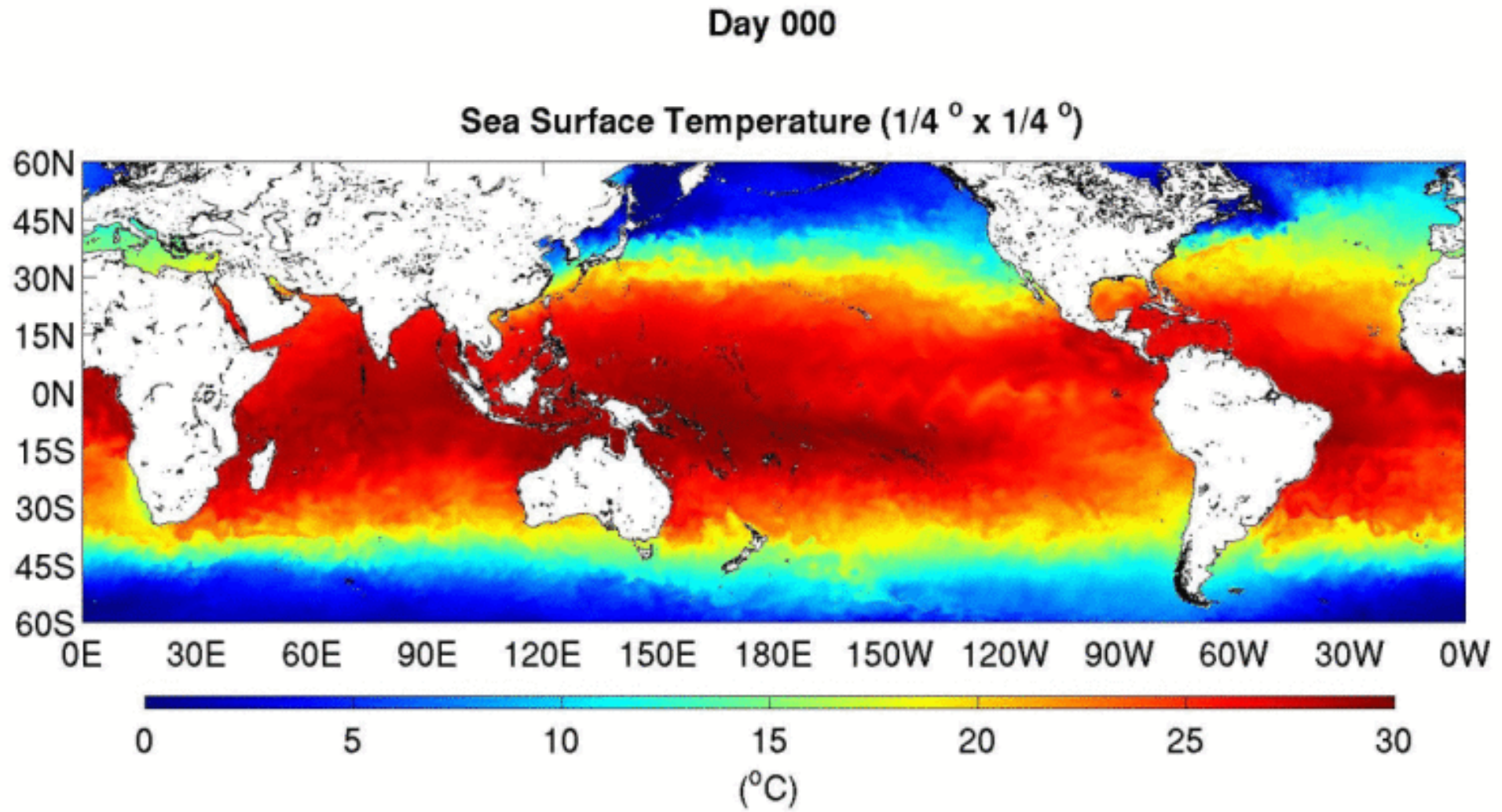
modelled ten-year standard deviation (year 41-50) of equivalent sea surface height (in cm)

1/4° Global Ocean Simulations

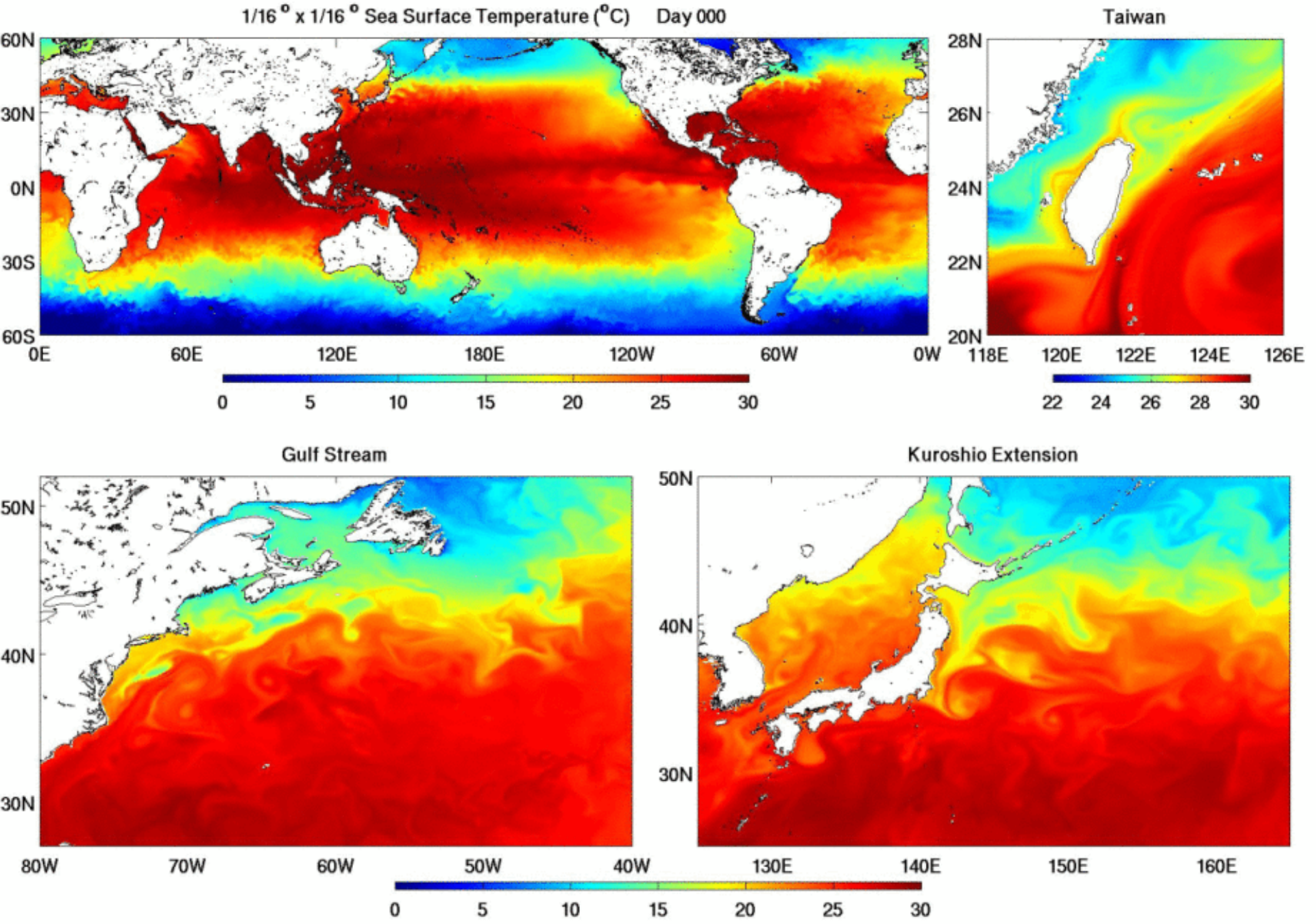
1/4 ° simulation grid sizes: 1442x720x26

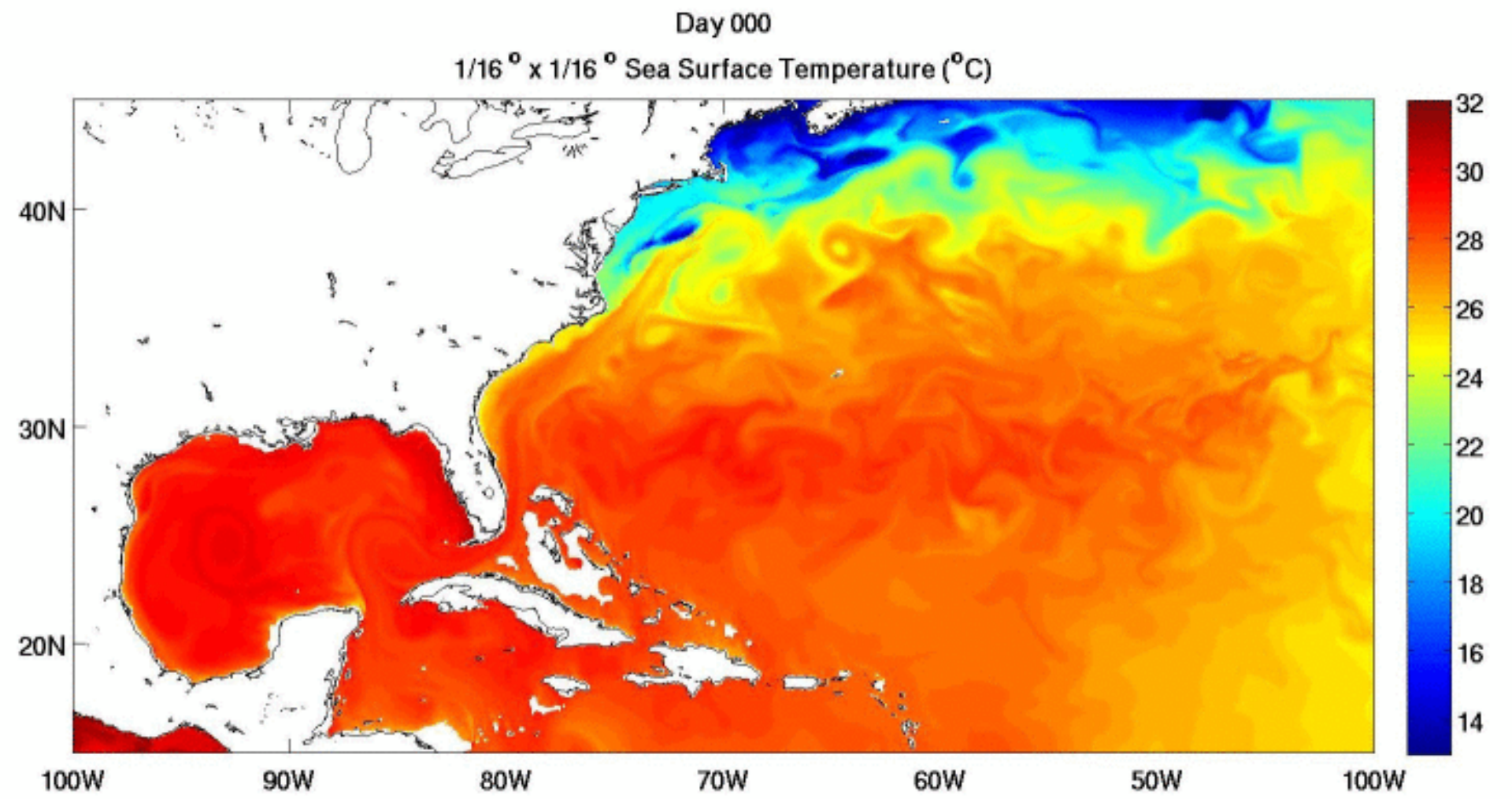


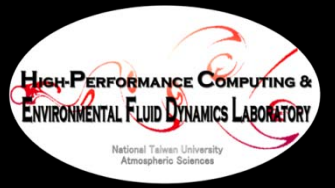
1/4 ° simulation grid sizes: 1442x720x26



1/16° Global Ocean Simulations


1/16 ° x 1/16 ° Sea Surface Temperature (°C) Day 000
60N
30N
0N
30S
60S
0E
60E
120E
180E
120W
60W
0W
0
5
10
15
20
25
30
Taiwan
28N
26N
24N
22N
20N
118E
120E
122E
124E
126E
22
24
26
28
30
Gulf Stream
50N
40N
30N
80W
70W
60W
50W
40W
Kuroshio Extension
50N
40N
30N
130E
140E
150E
160E
0
5
10
15
20
25
30

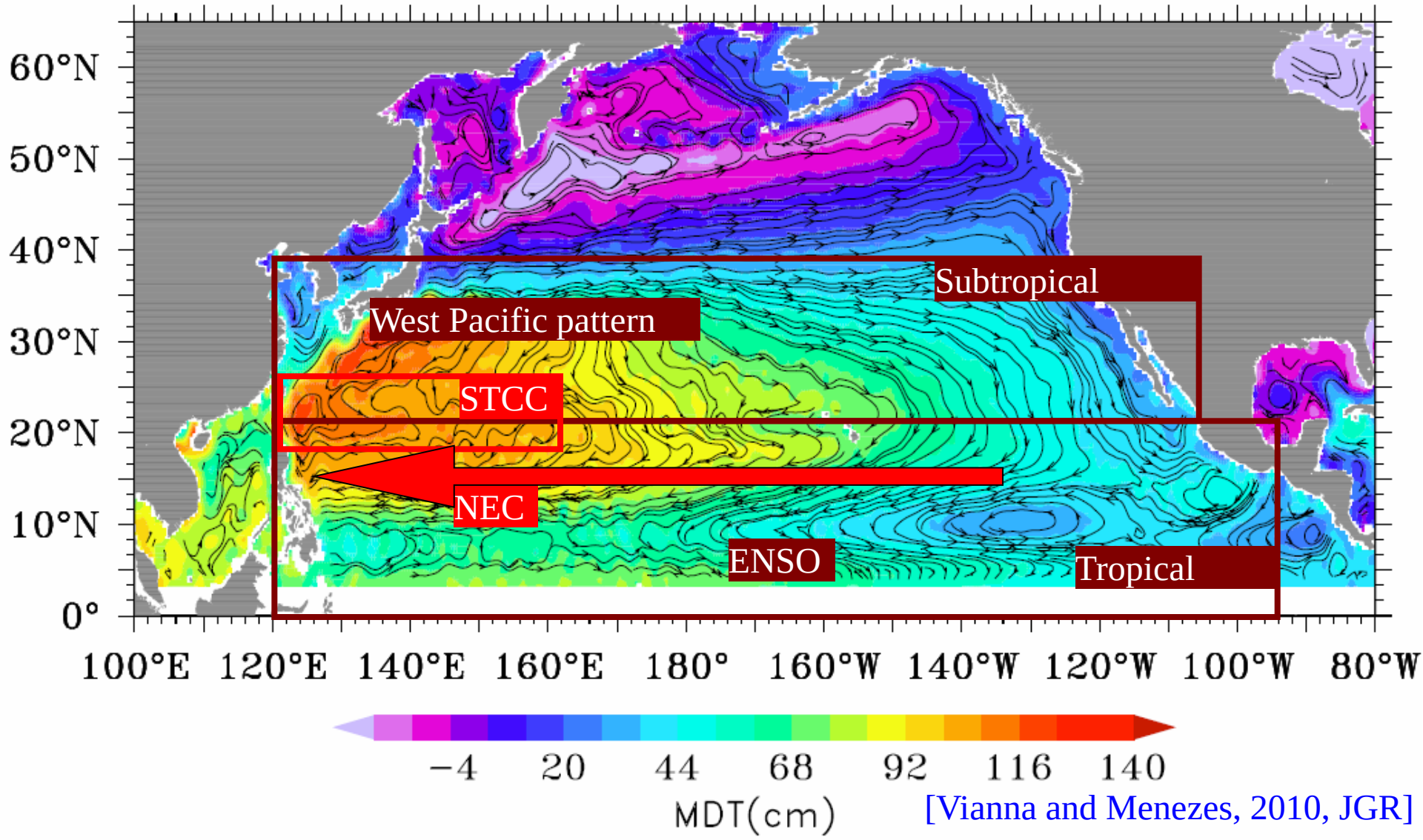

Day 000
1/16 ° x 1/16 ° Sea Surface Temperature (°C)
40N
30N
20N
100W
90W
80W
70W
60W
50W
100W
32
30
28
26
24
22
20
18
16
14



Thank You

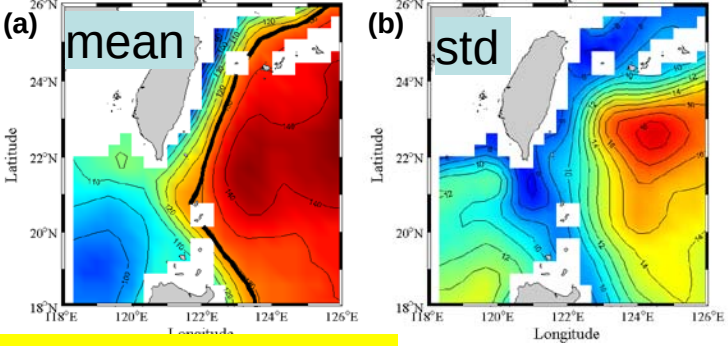
Customized By EFDL

Possible Source of the KT

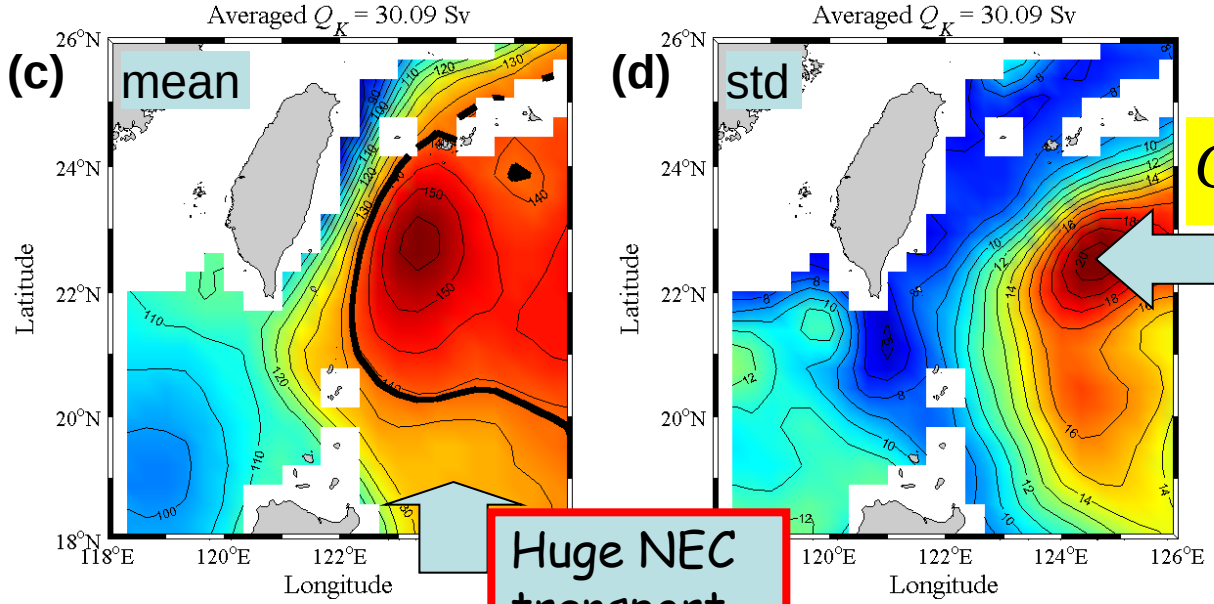


[Vianna and Menezes, 2010, JGR]

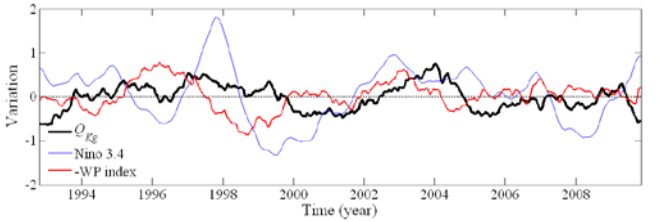
Different KT Phases

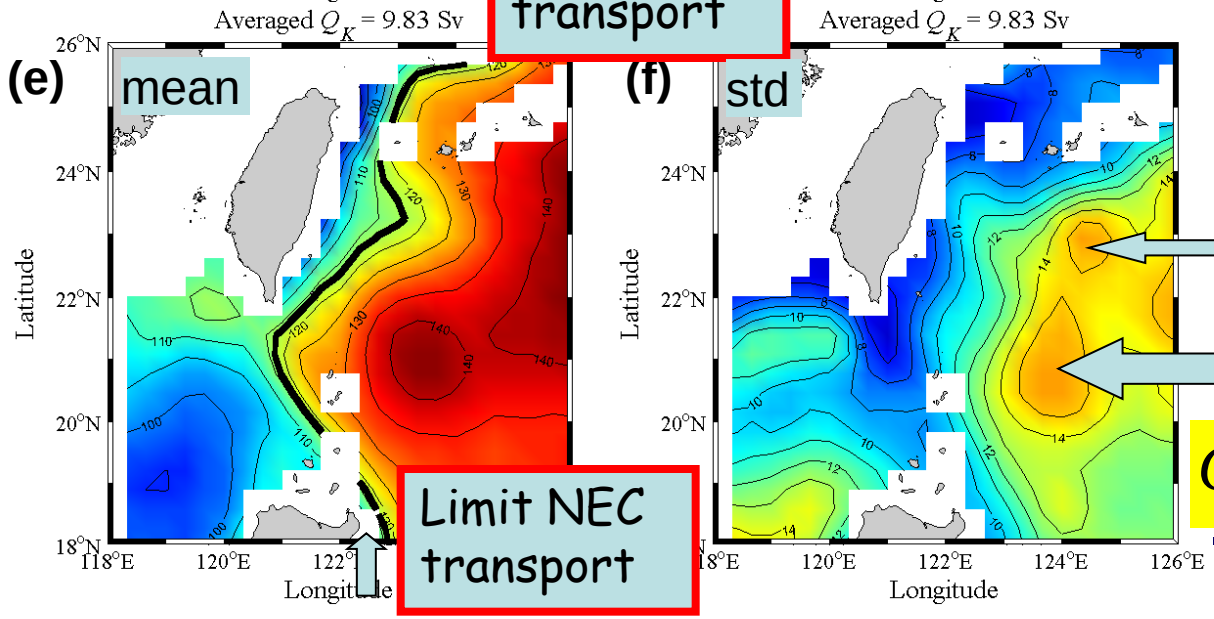


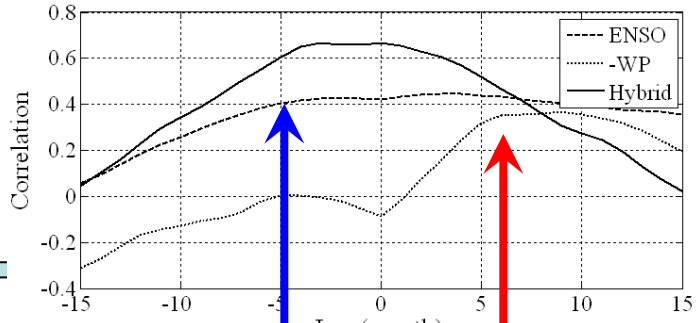
$$Q_{Kg} > \bar{Q}_{Kg} + \sigma_Q$$



Huge NEC transport







KT vs. -WP

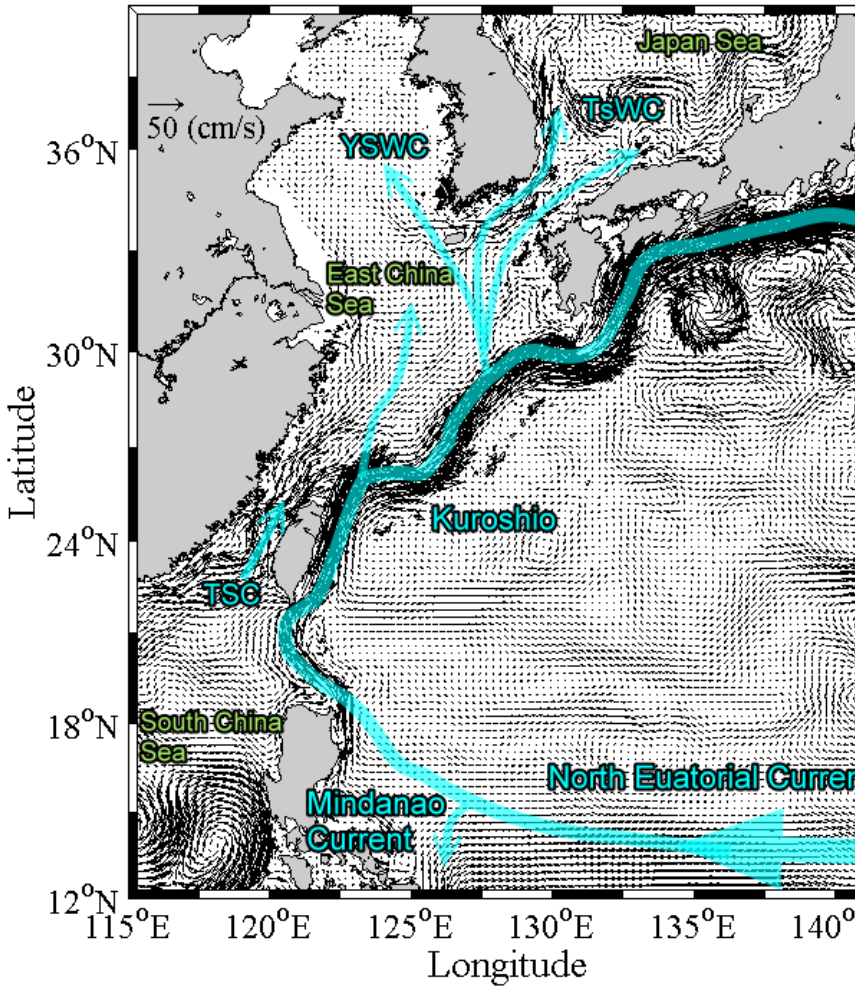
KT vs. ENSO

Limit NEC transport

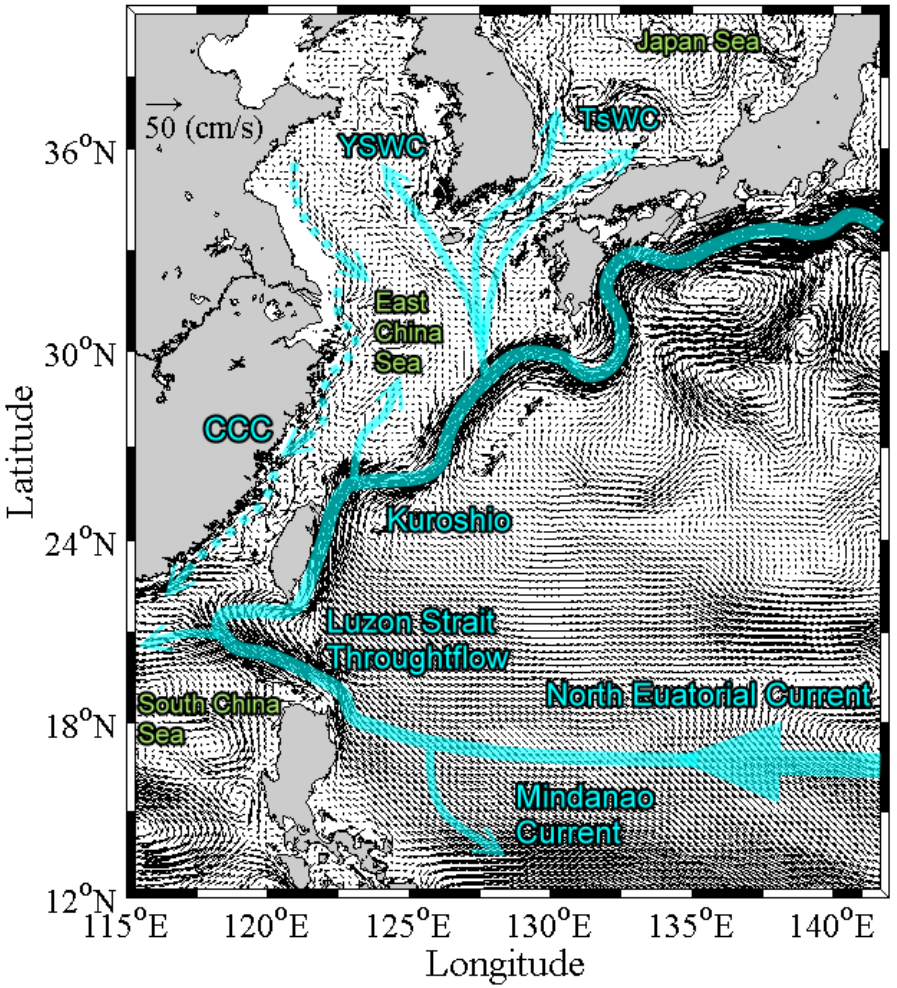
$$Q_{Kg} < \bar{Q}_{Kg} - \sigma_Q$$

HC/EFDL, NTU

General seasonal circulation pattern-DUPOM

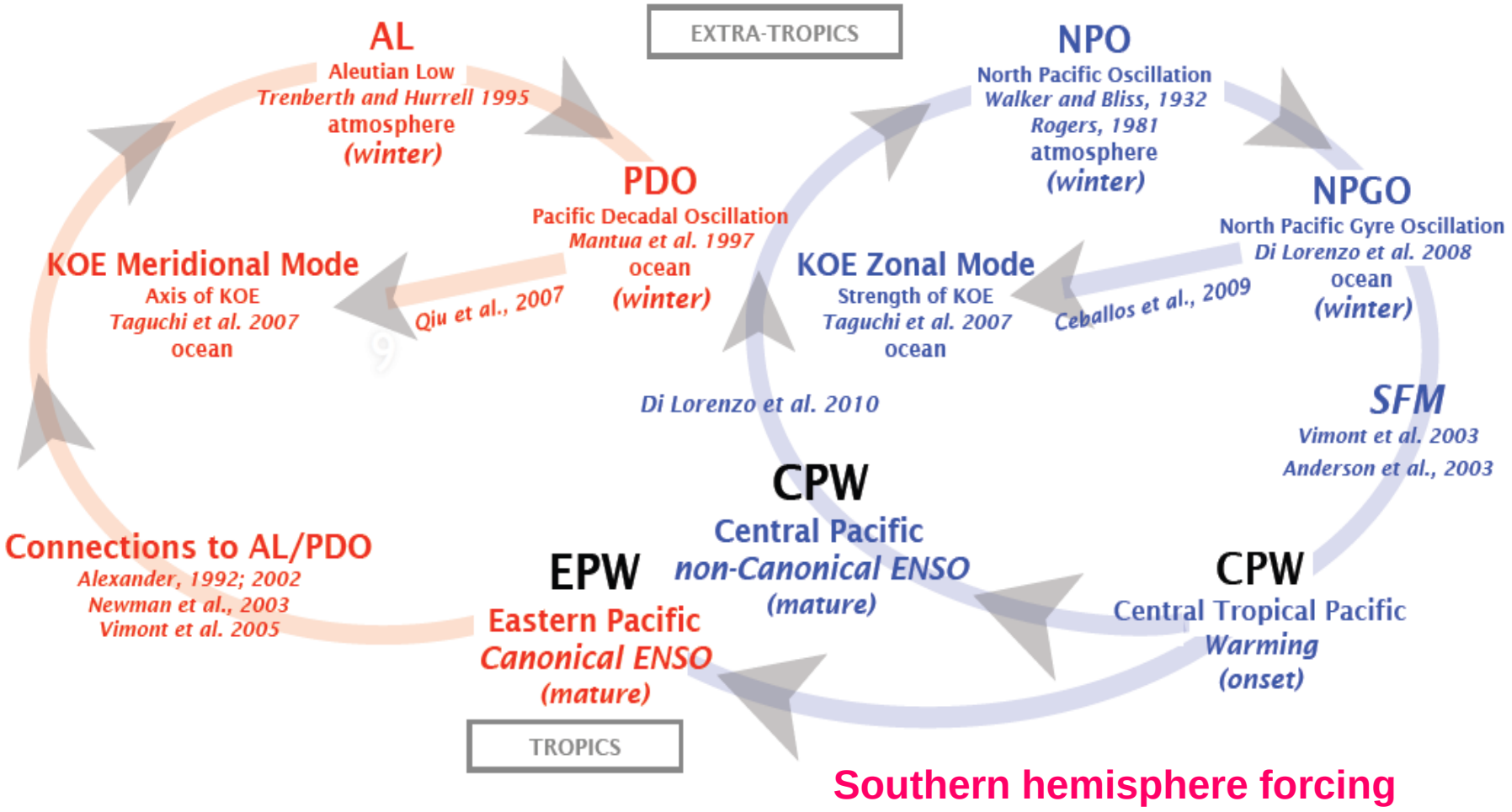


Summer

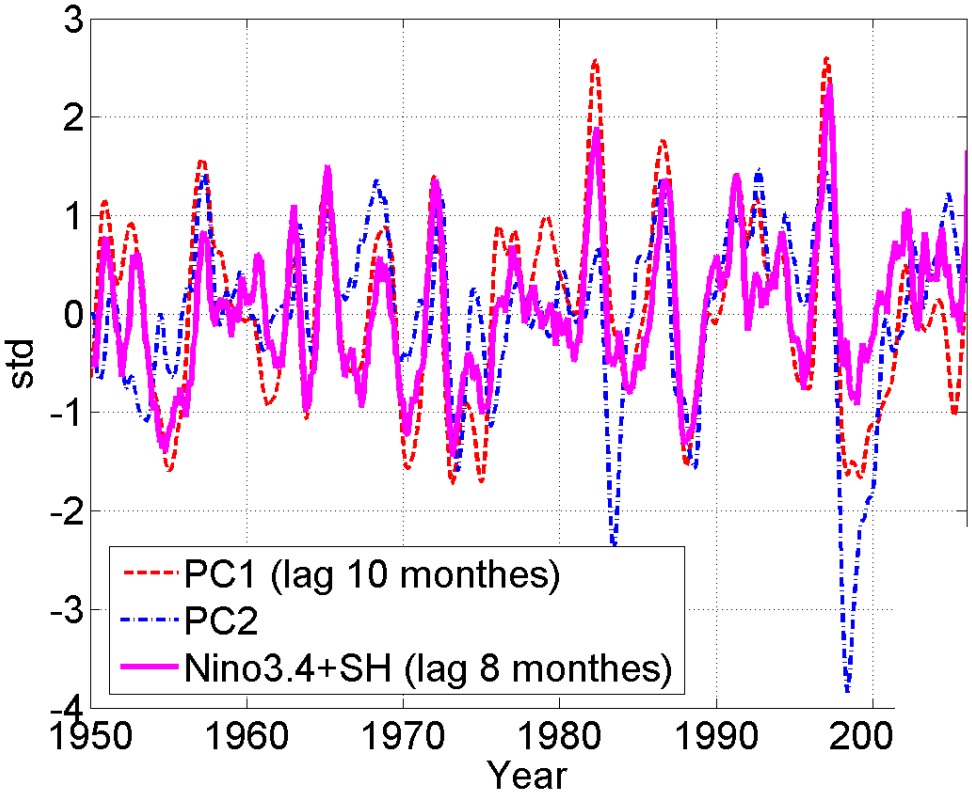


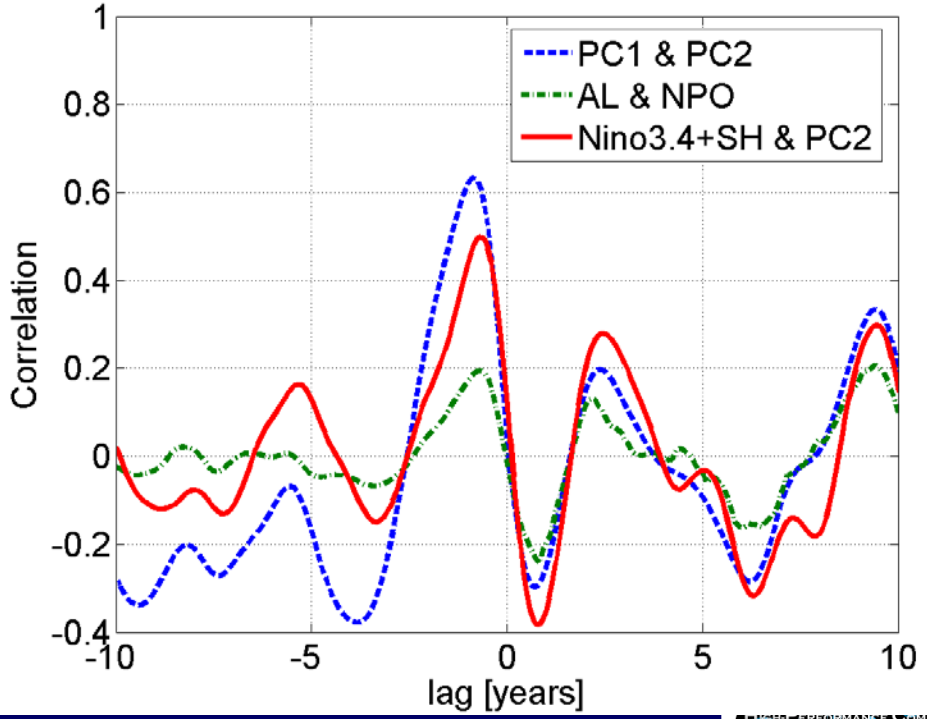
Winter

Framework for Pacific Climate Variability



Di Lorenzo et al, *ENSO and the North Pacific Gyre Oscillation: an integrated view of Pacific decadal dynamics*



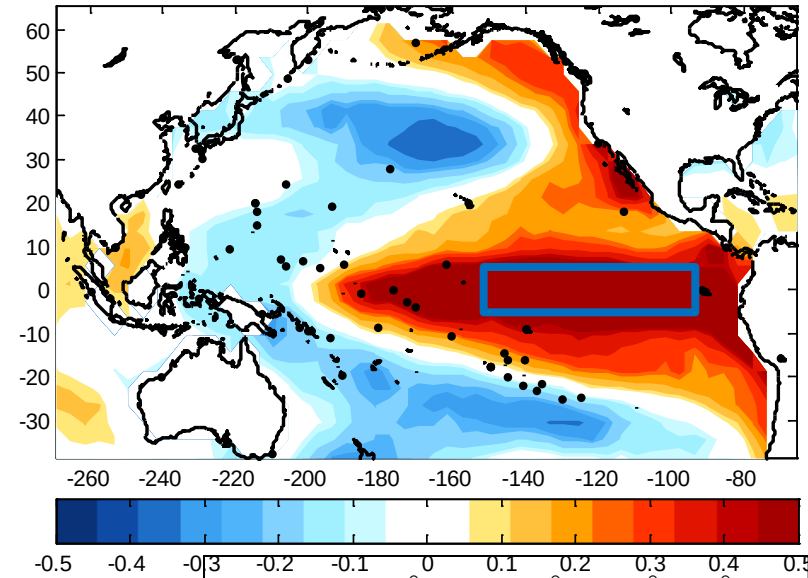


SSTa is associated with El Nino-Modoki

SSTa patterns (PC1) leads ENSO anomalies by ~8 months

PC1 (ENSO) lags PC2

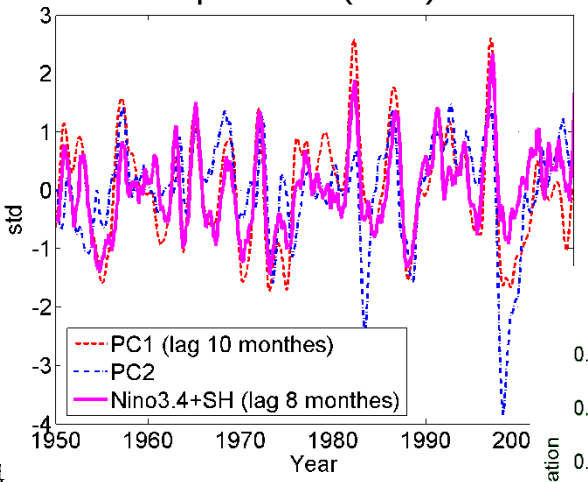
EOF1 (HadISSTA from 1951-2009; 34%)



nino3 (90°W-150°W, 5°S-5°N)

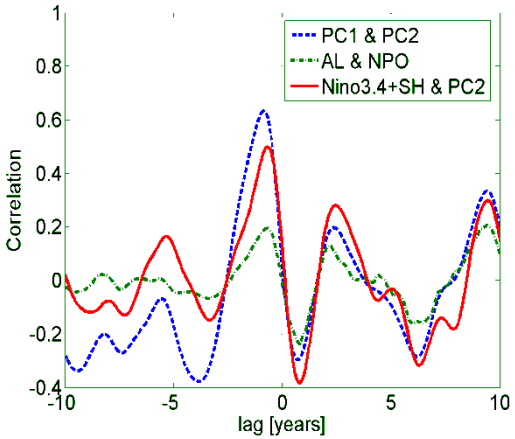
SSTa is associated with El Nino-Modoki

SSTa patterns (PC1) leads ENSO anomalies by ~8 months

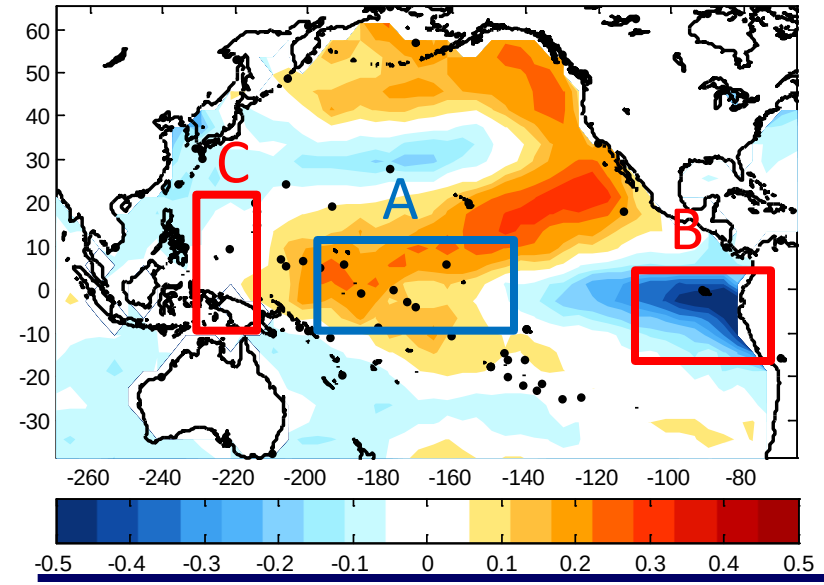


NINO3 = $[SSTA]_{nino3}$

PC1 (ENSO) lags PC2



EOF2 (HadISSTA from 1951-2009; 8%)



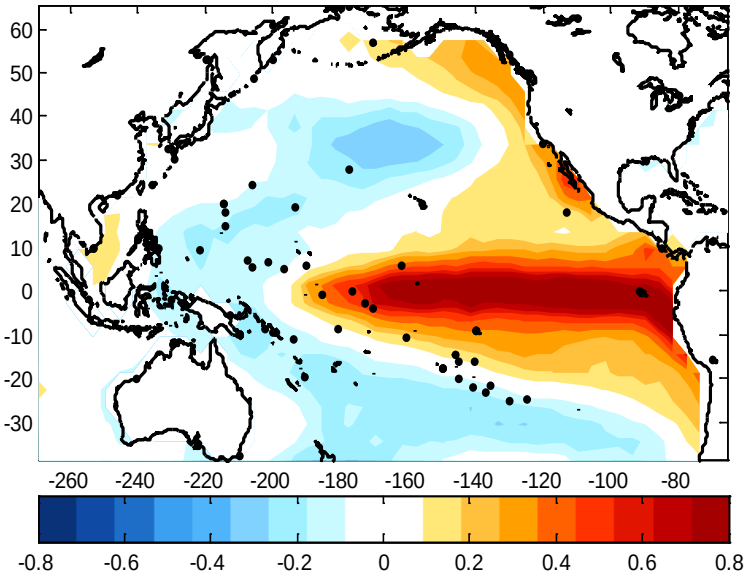
EMI = $[SSTA]_A$ - 0.5*$[SSTA]_B$ - 0.5*$[SSTA]_C$

A (165°E-140°W, 10°S-10°N)
B (110°W-70°W, 15°S-5°N)
C (125°E-145°E, 10°S-20°N)

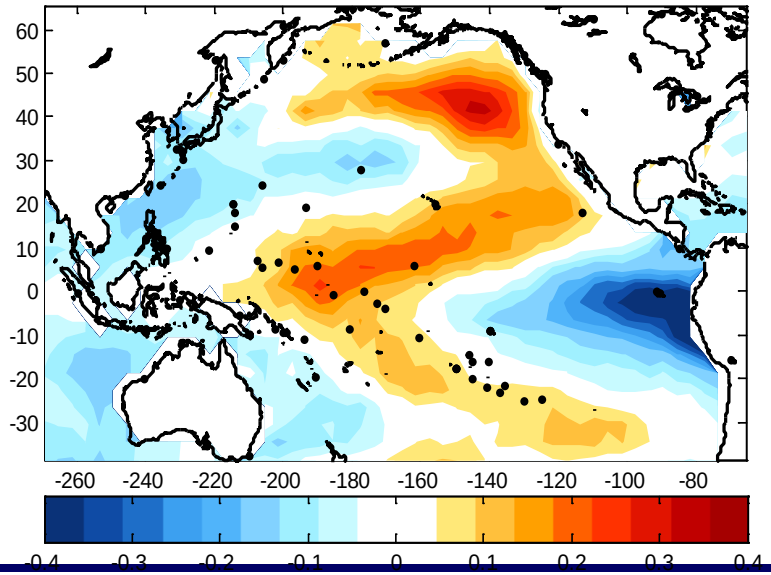
Weng et al. 2008

Observation

SST 1 (30%)

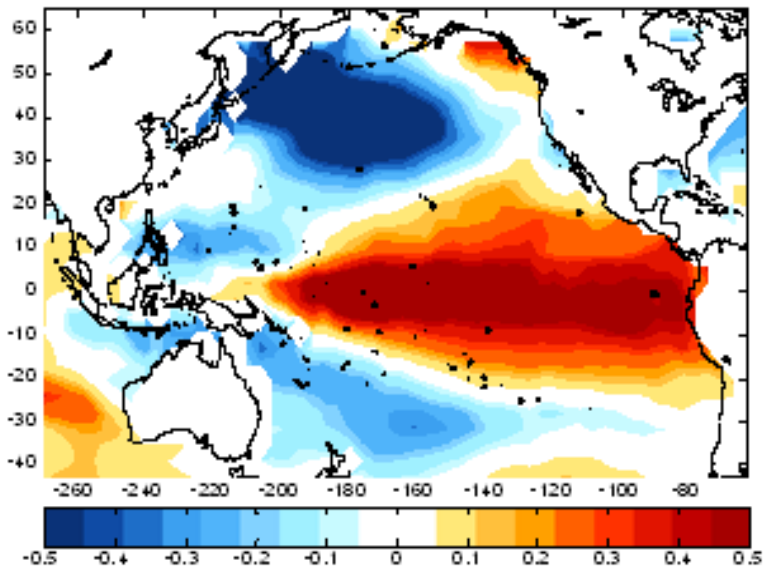


SST 2 (10%)

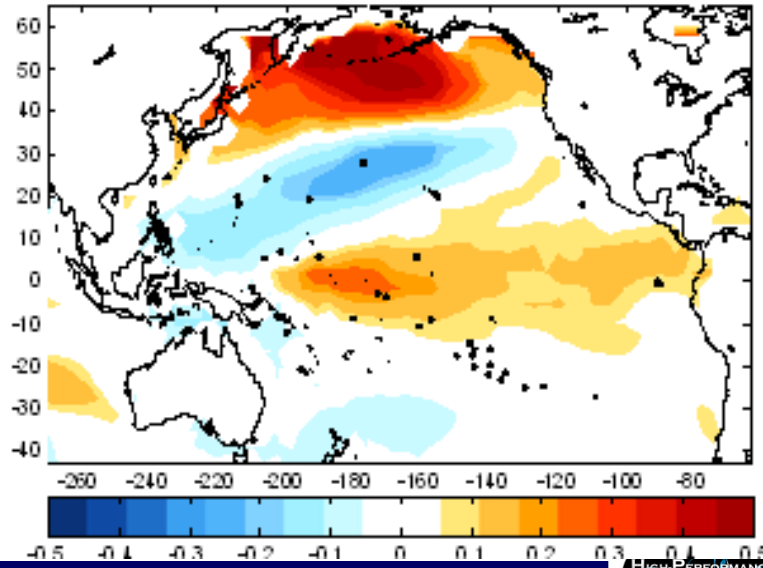


Model

SST 1 (23%)

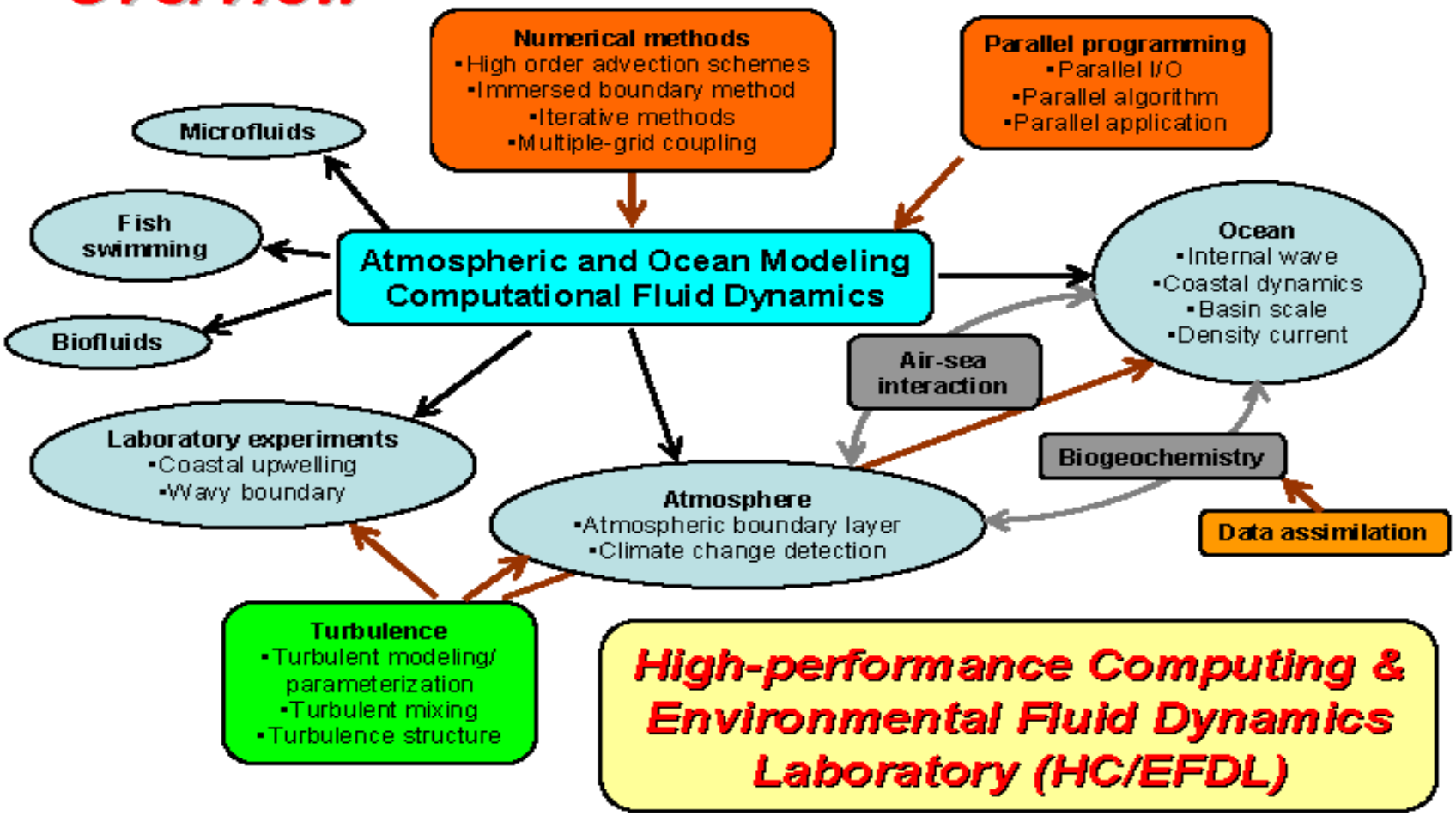


SST 2 (7%)



Overview

高速計算與環境流體動力實驗室

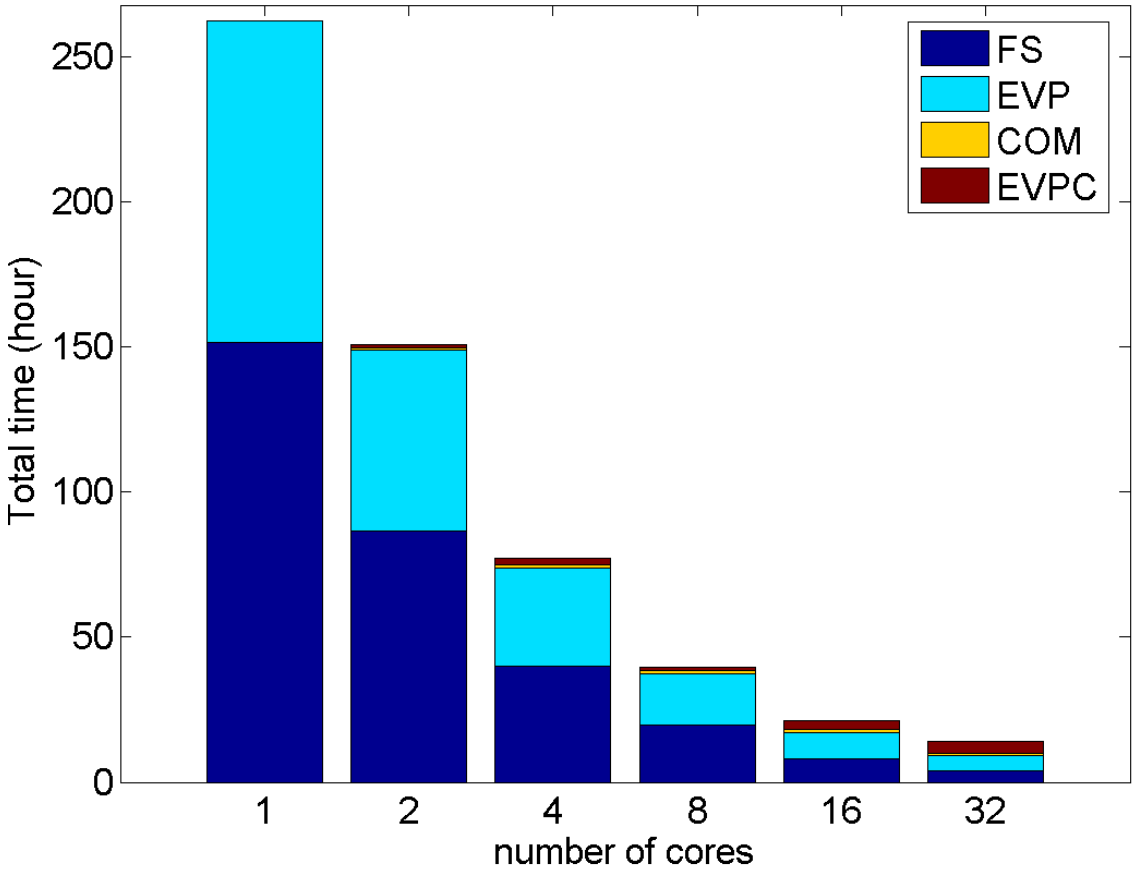


Questions……?

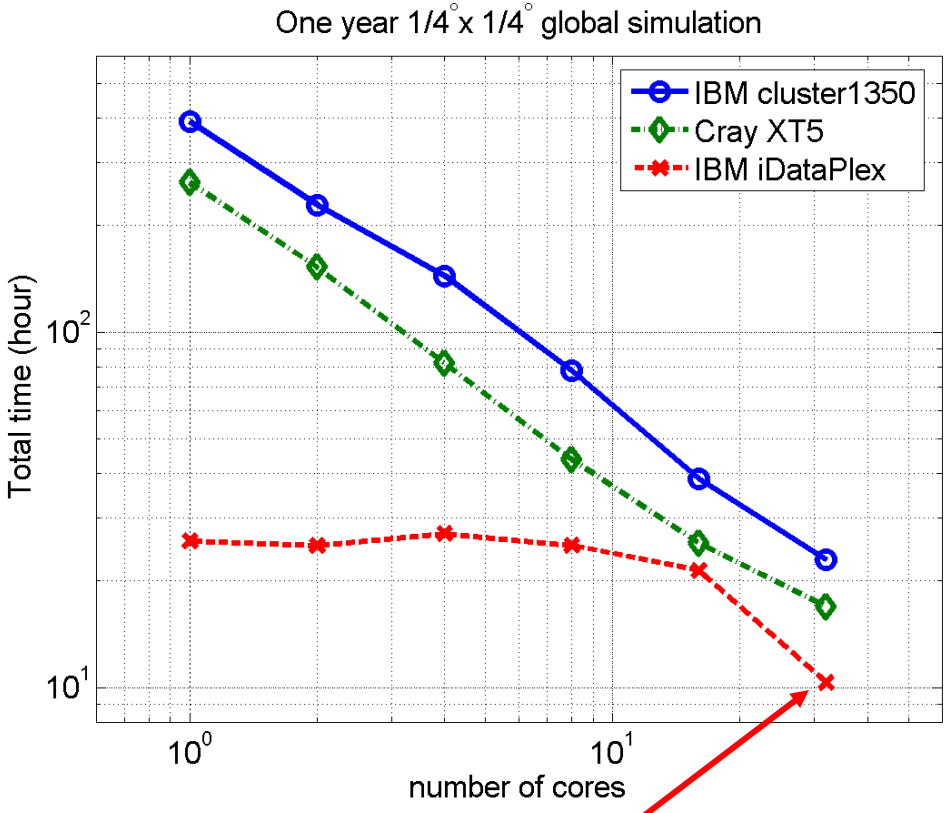
Parallel performance

FS: simulation time
EVP: pressure solver time

COM: Other Communication
EVPC: Communication in EVP solver

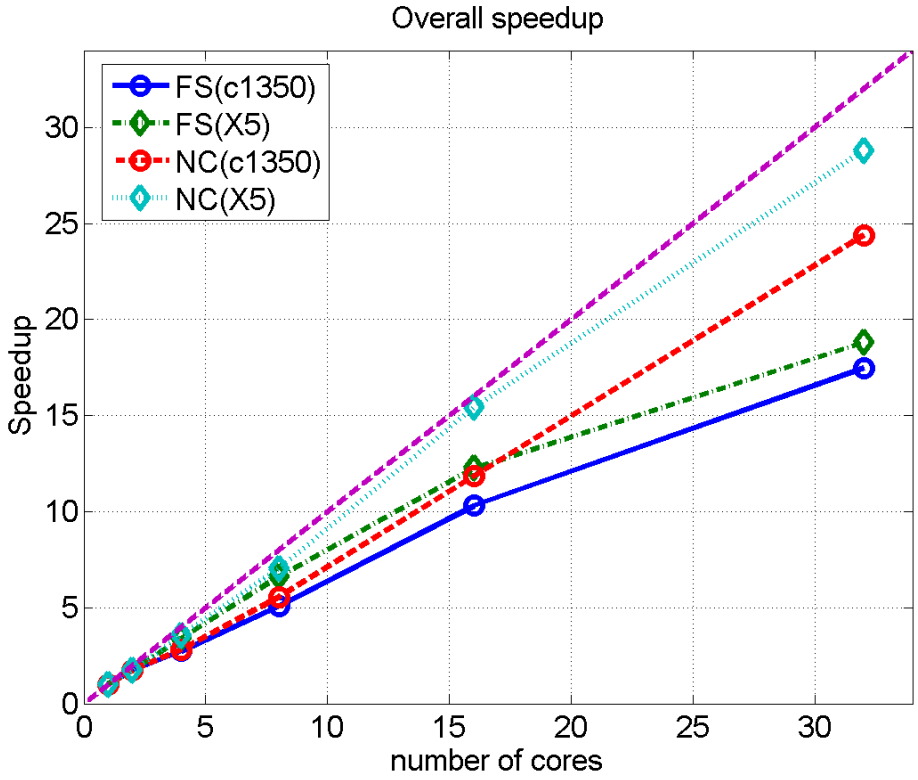


Parallel speedup

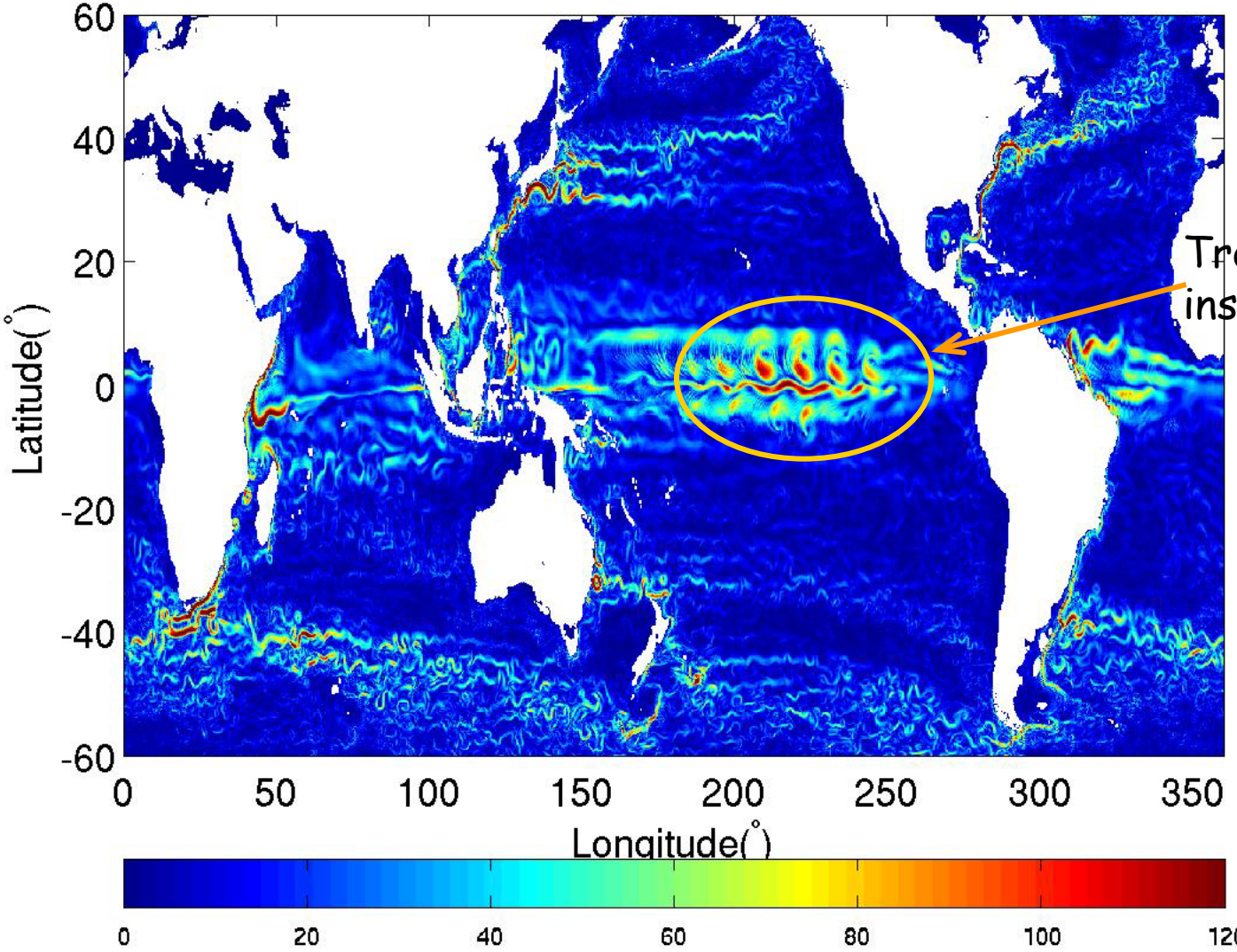


Roughly 10 CPU hrs/per simulation year

FS: all computation
NC: full computation without the communication

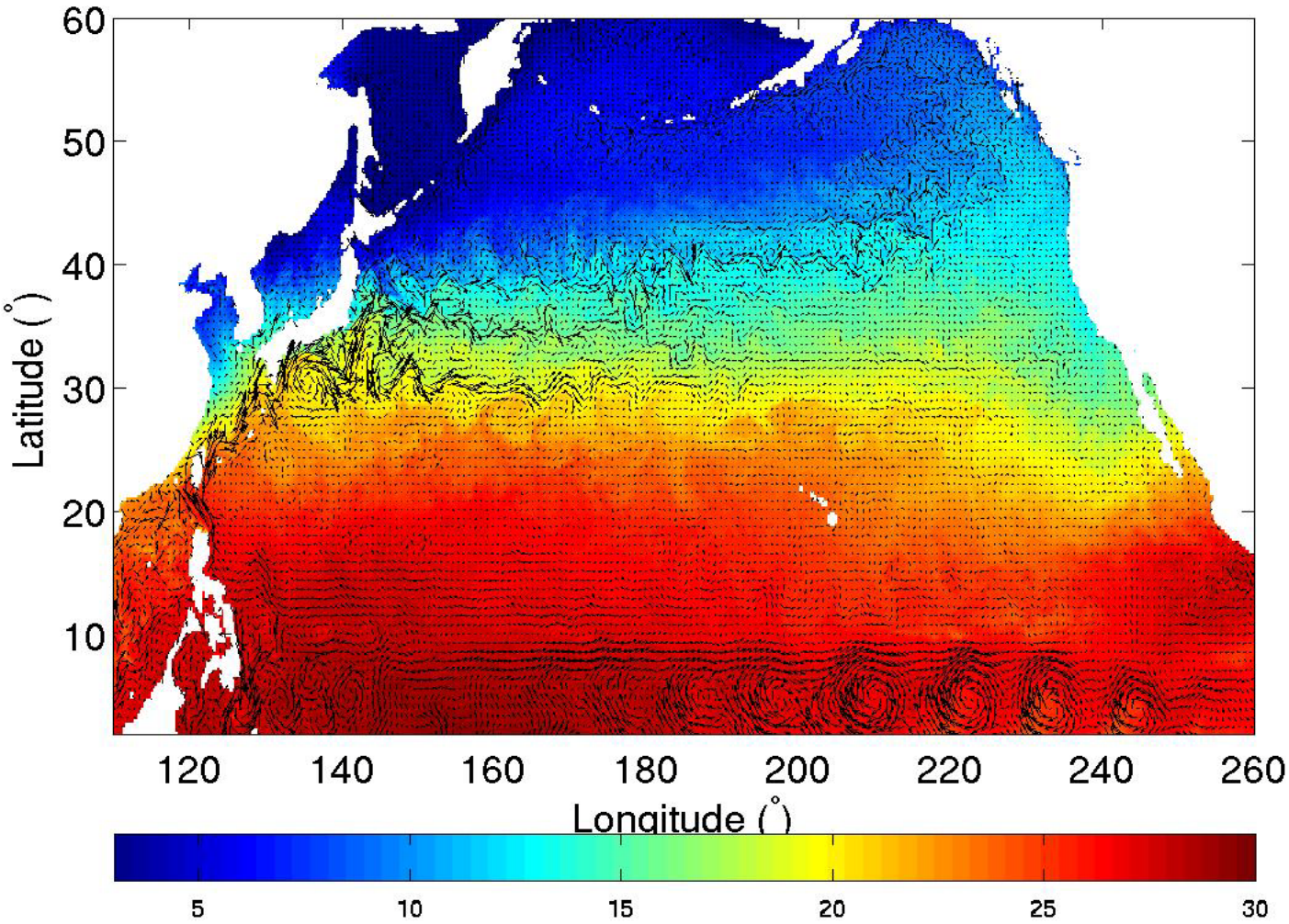


1/4° x 1/4° global resolution (domain 1442x720x26)



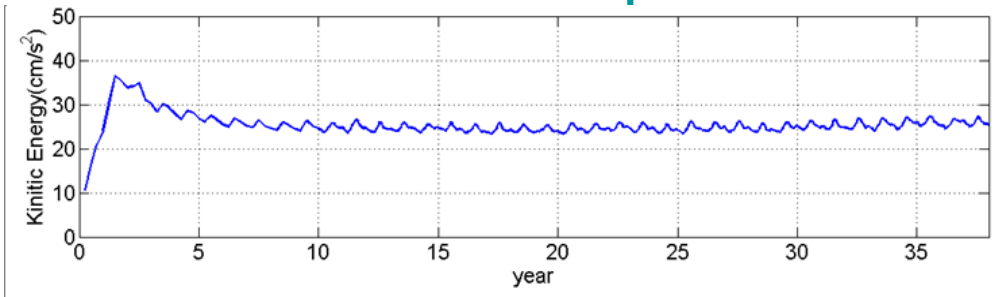
Global velocity speed field (day 5, Year 49)

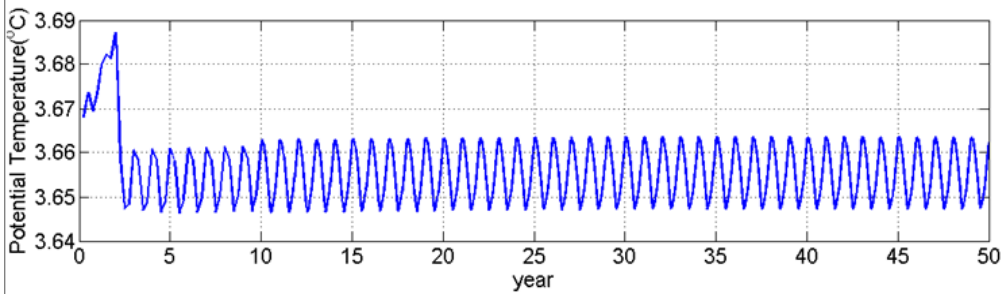
1/4° x 1/4° global resolution (domain 1442x720x26)

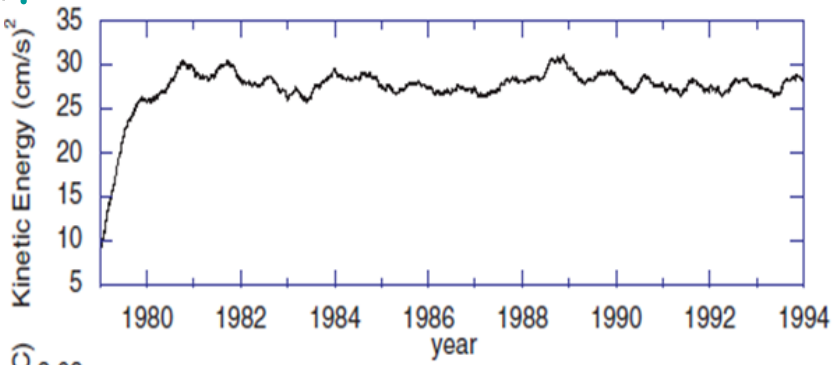


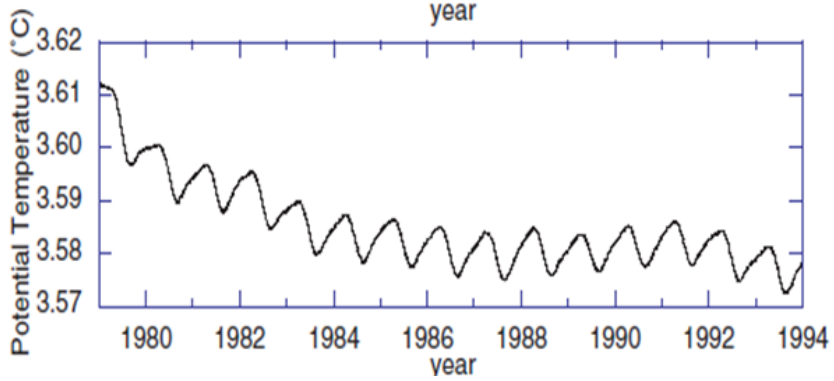
North Pacific temperature and velocity field (day 5, Year 49)

Time evolution of globally averaged Total Kinetic Energy and potential temperature

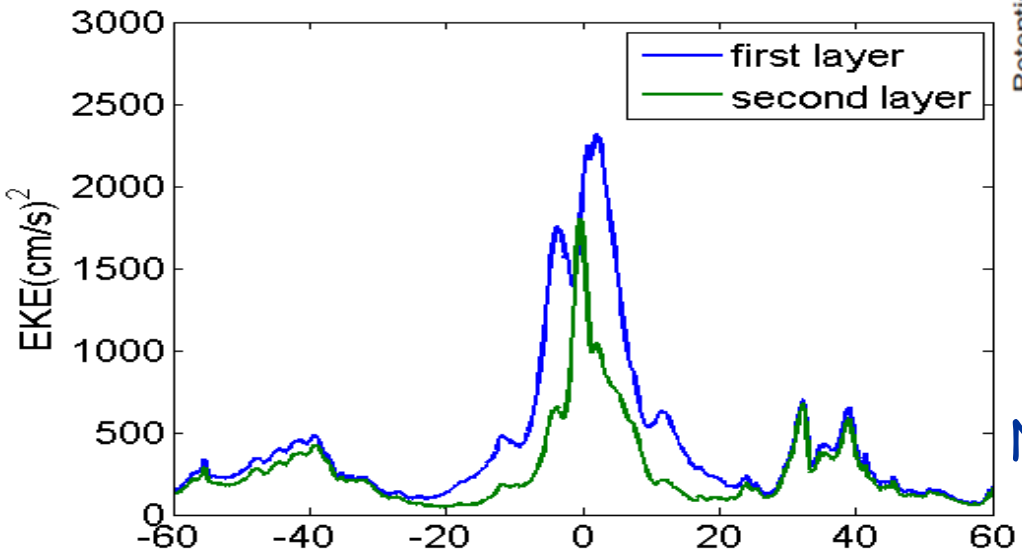






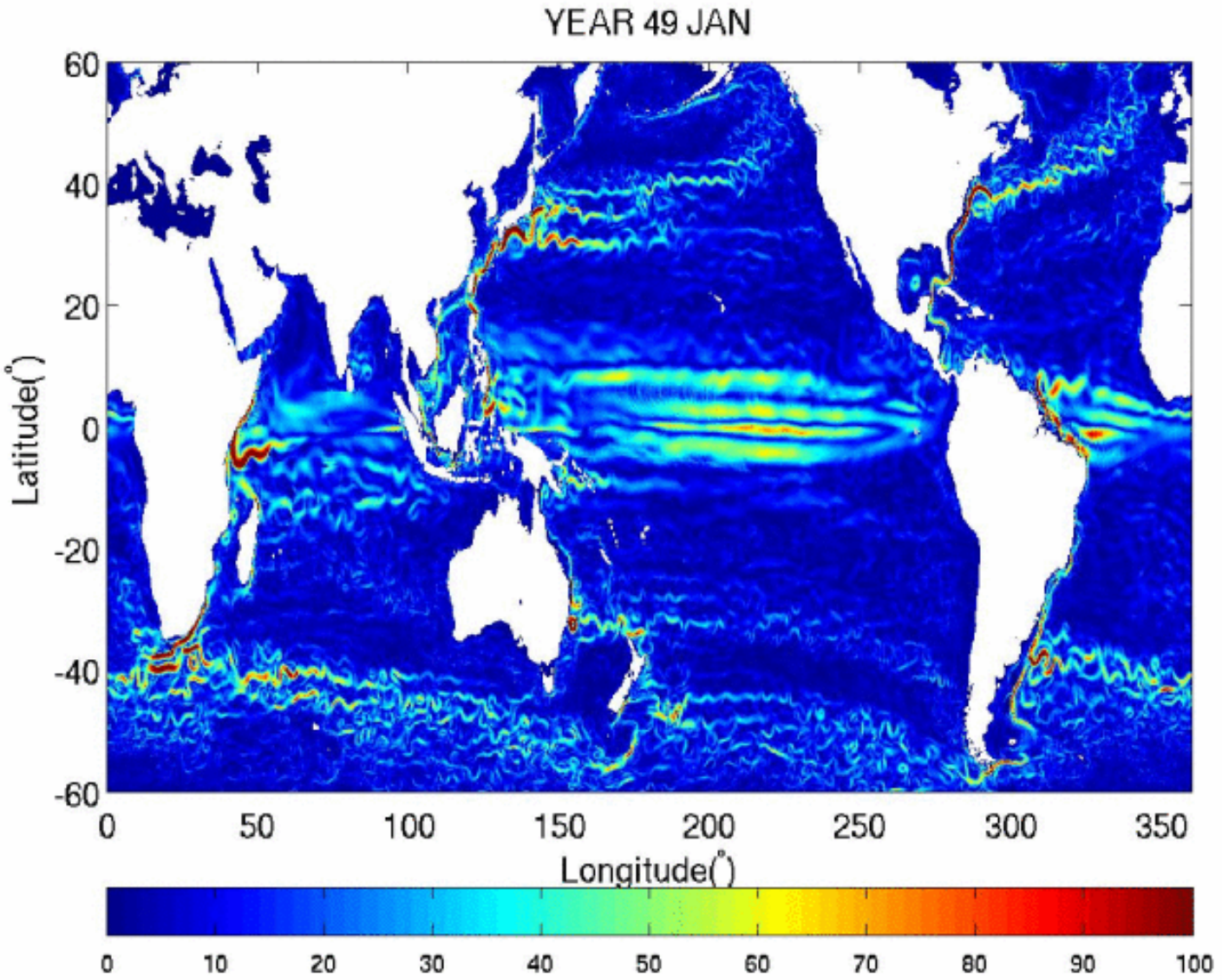


Maltrud and McClean (2005)



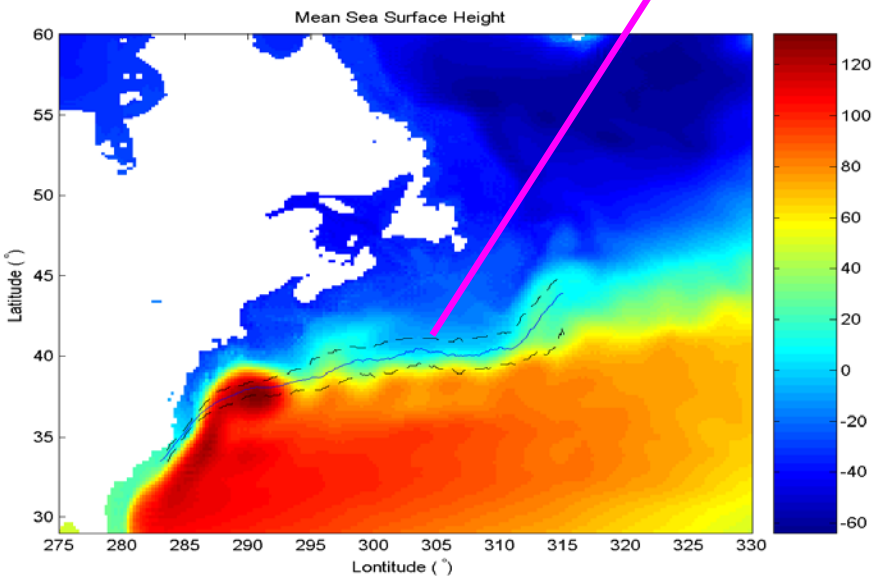
Near-surface Eddy Kinetic Energy

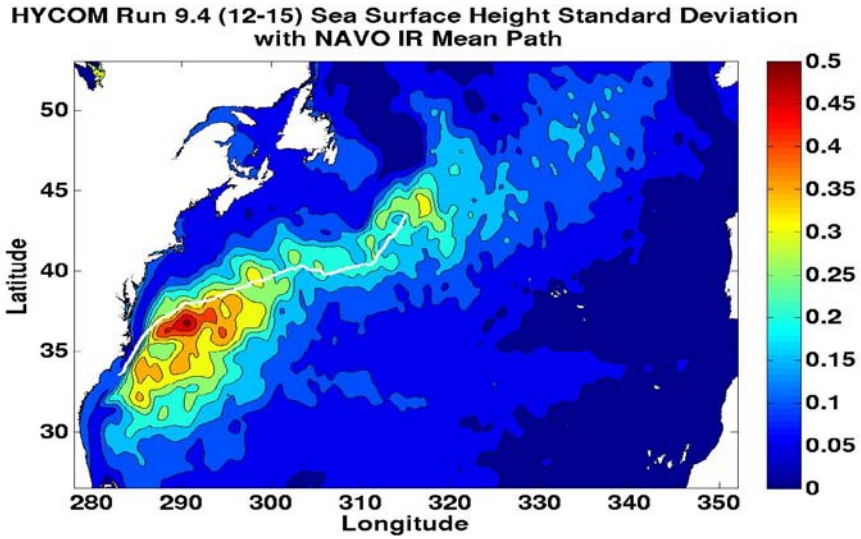
Animation of global surface velocity speed



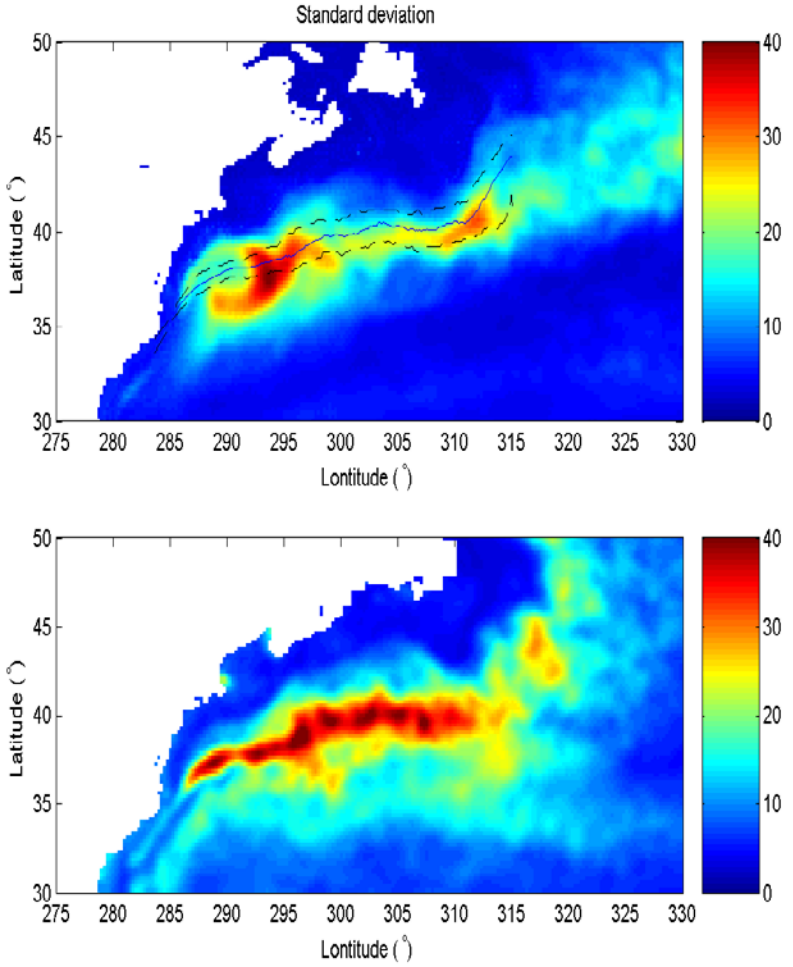
Gulf Stream

The mean Gulf Stream IR northwall pathway ±1σ (standard deviation) by Cornillon and Sirkes



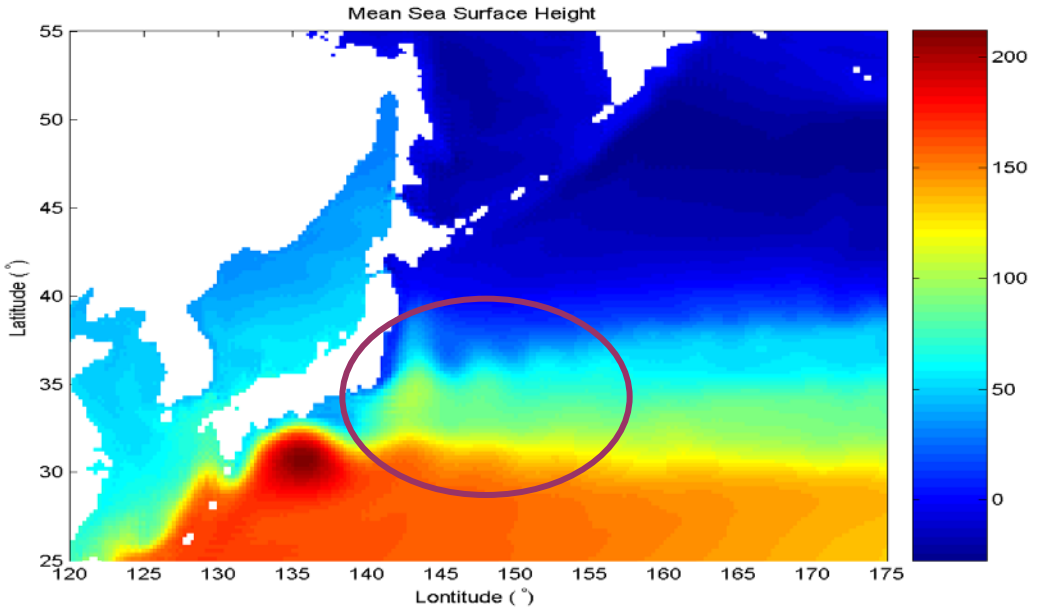


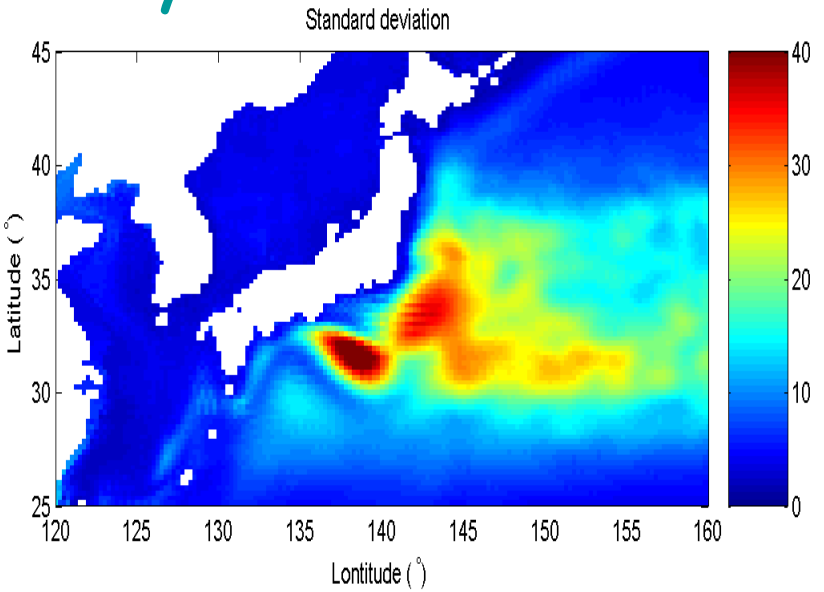
Courtesy of Jim Richman (NRL)

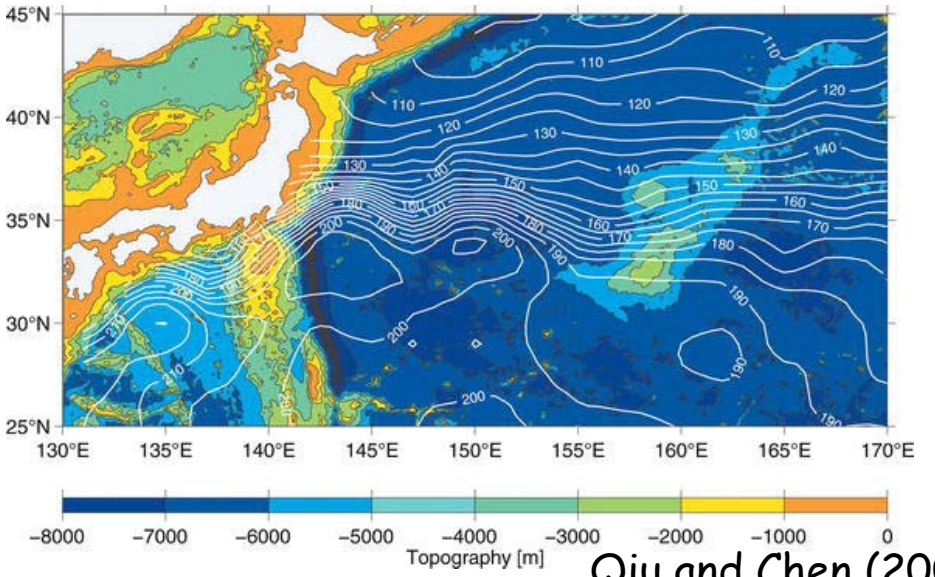


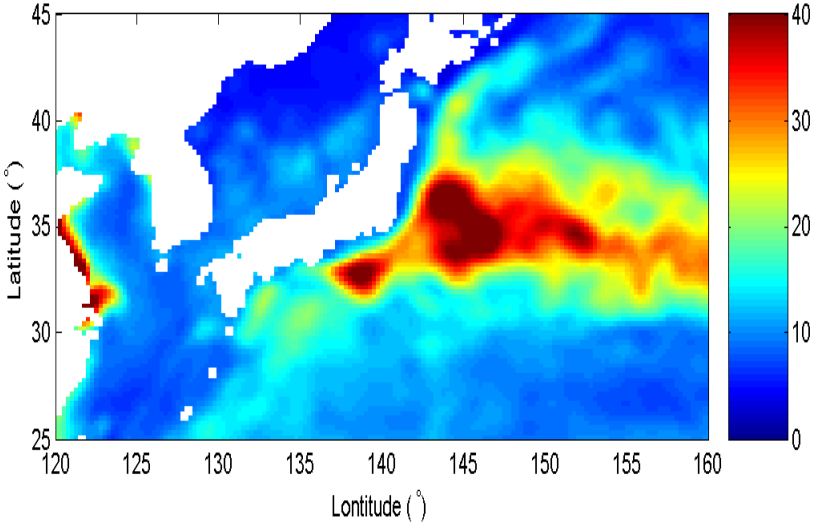
modelled ten-year standard deviation (year 41-50) of equivalent sea surface height (in cm)

Kuroshio Current System



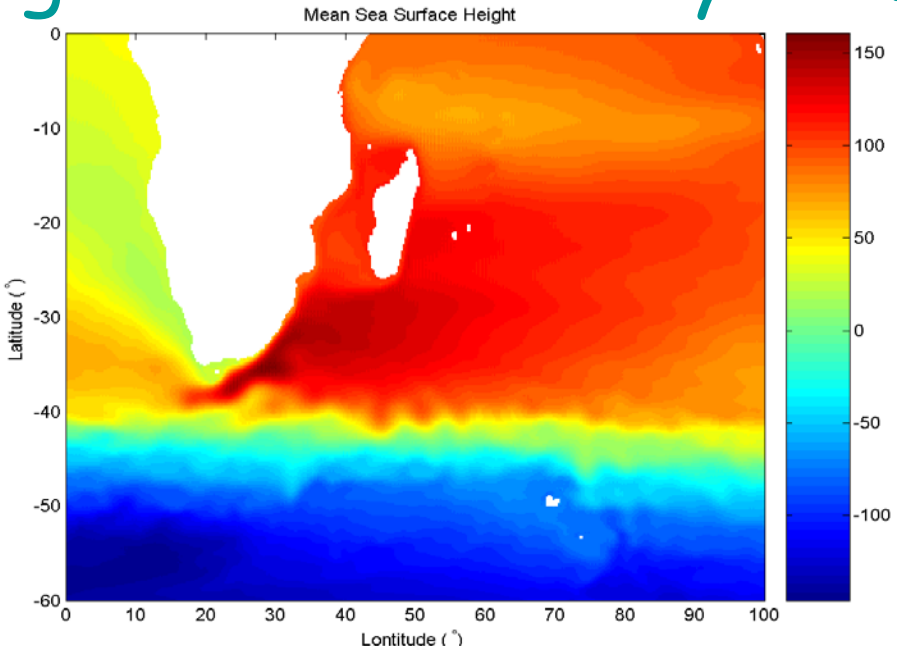


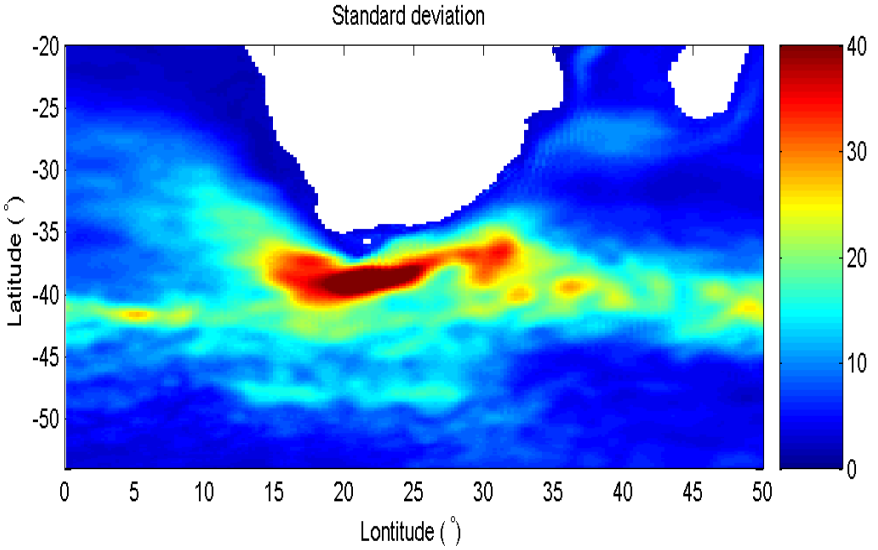


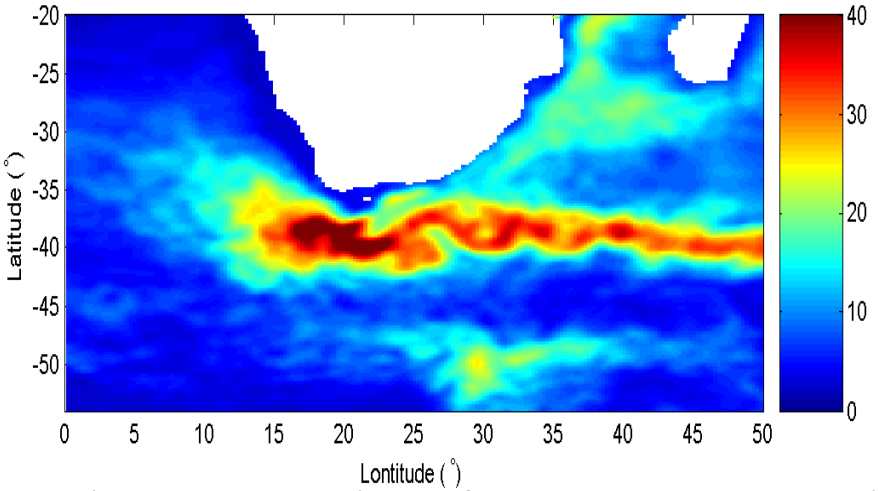


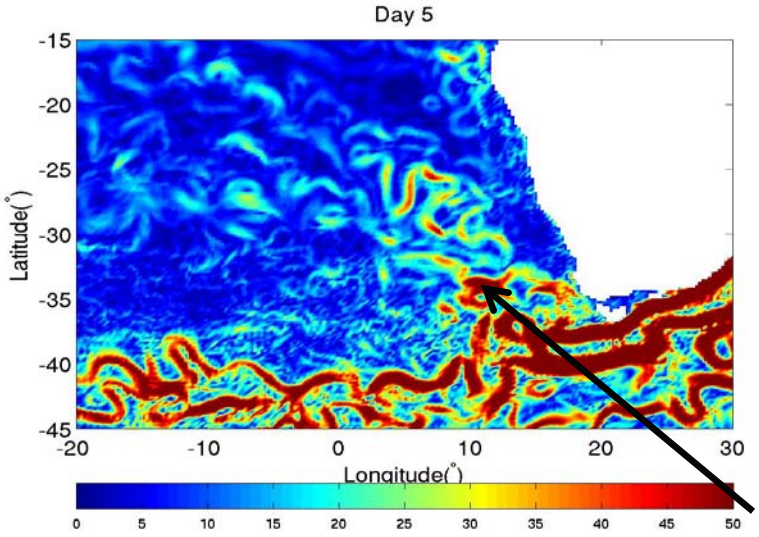
Qiu and Chen (2005)

Agulhas Current System









5-day averaged surface current speed (cm/s) in Cape Basin

Retroflection of the Agulhas Current

Summary

- High-resolution Parallel Domain-decomposed TaIwan Multi-scale Community Ocean Model (PD-TIMCOM) is developed
  - Based on TIMCOM
  - Based on an efficient parallel EVP solver
  - Ideal (scalable) for parallel domain-decomposition
- Reasonable mean, standard deviation and skewness states
- Eddy-resolving global circulation patterns
- Fifty year simulation is almost completed
- Further validations and extremely high-resolution (1/16°) in Global Oceans and investigate the global ocean climate

Governing Equations

λ: the longitudinal variable
ϕ: the latitudinal variable
z: the vertical variable

Continuity eqn. $$\frac{1}{R\cos\phi}\left(\frac{\partial u}{\partial \lambda}+\frac{\partial (v\cos\phi)}{\partial \phi}\right)+\frac{\partial \omega}{\partial z}=0$$

Momentum eqn.

$$\frac{\partial u}{\partial t}=-\mathcal{L}u+\left(f+\frac{u\tan\phi}{R}\right)v-\frac{1}{\rho_0 R\cos\phi}\frac{\partial p}{\partial \lambda}+D_m u+\frac{\partial}{\partial z}\left(A_u\frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t}=-\mathcal{L}v-\left(f+\frac{u\tan\phi}{R}\right)u-\frac{1}{\rho_0 R}\frac{\partial p}{\partial \phi}+D_m v+\frac{\partial}{\partial z}\left(A_v\frac{\partial u}{\partial z}\right)$$

Conservation eqn. for temperature and salinity

$$\frac{\partial T}{\partial t}=-\mathcal{L}T+D_h T+\frac{\partial}{\partial z}\left(K_T\frac{\partial T}{\partial z}\right)$$

Eqn. of State

$$\rho=\rho(S,T,p)$$

Hydrostatic Eqn. $$\frac{\partial p}{\partial z}=-(\rho-\bar{\rho})g$$

$$D_{m(h)}=\frac{A_{m(h)}}{R^2}\left(\frac{1}{\cos^2\phi}\frac{\partial^2}{\partial\lambda^2}-\tan\phi\frac{\partial}{\partial\phi}+\frac{\partial^2}{\partial\phi^2}\right)$$

$$\mathcal{L}=\frac{u}{R\cos\phi}\frac{\partial}{\partial\lambda}+\frac{v}{R}\frac{\partial}{\partial\phi}+\omega\frac{\partial}{\partial z}$$

Parallel domain-decomposed Taiwan Multi-scale Community Ocean Model (PD-TIMCOM)

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National Taiwan University
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Acknowledgement: computing resources from NCHC, Taiwan and NERSC, U