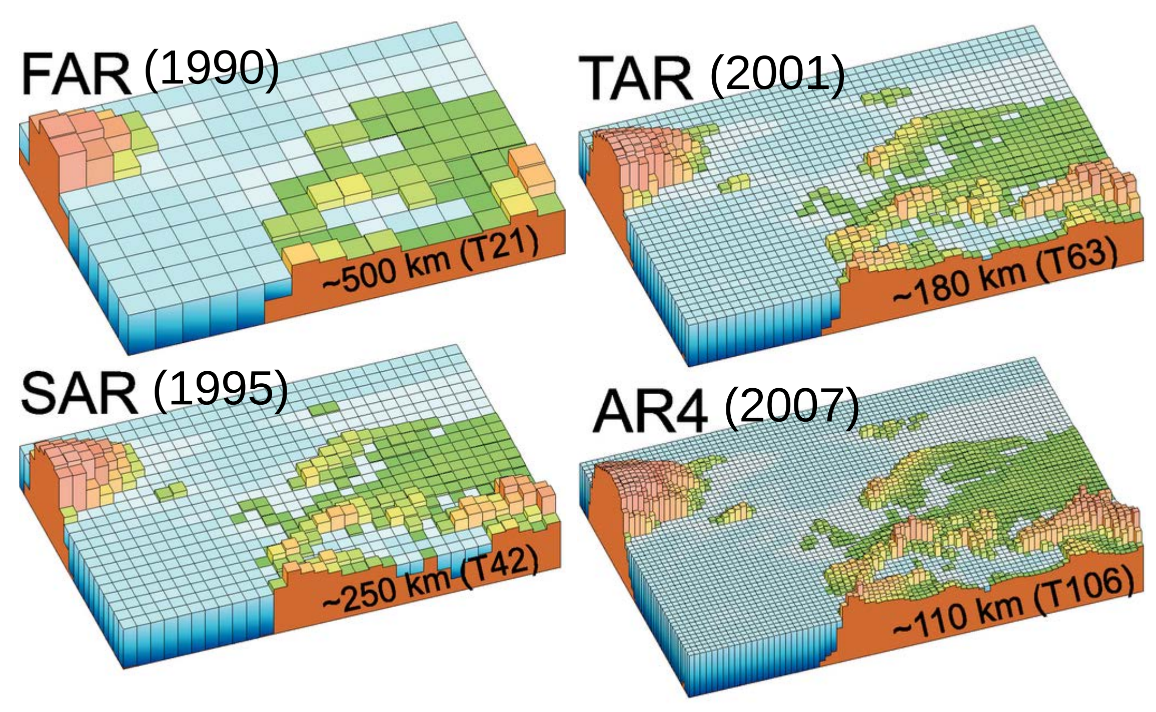
HIGH-RESOLUTION EFFORT



From IPCC Fourth Assessment Report: Climate Change 2007
http://www.ipcc.ch/

Yuhei Takaya

Climate Prediction Division
Japan Meteorological Agency

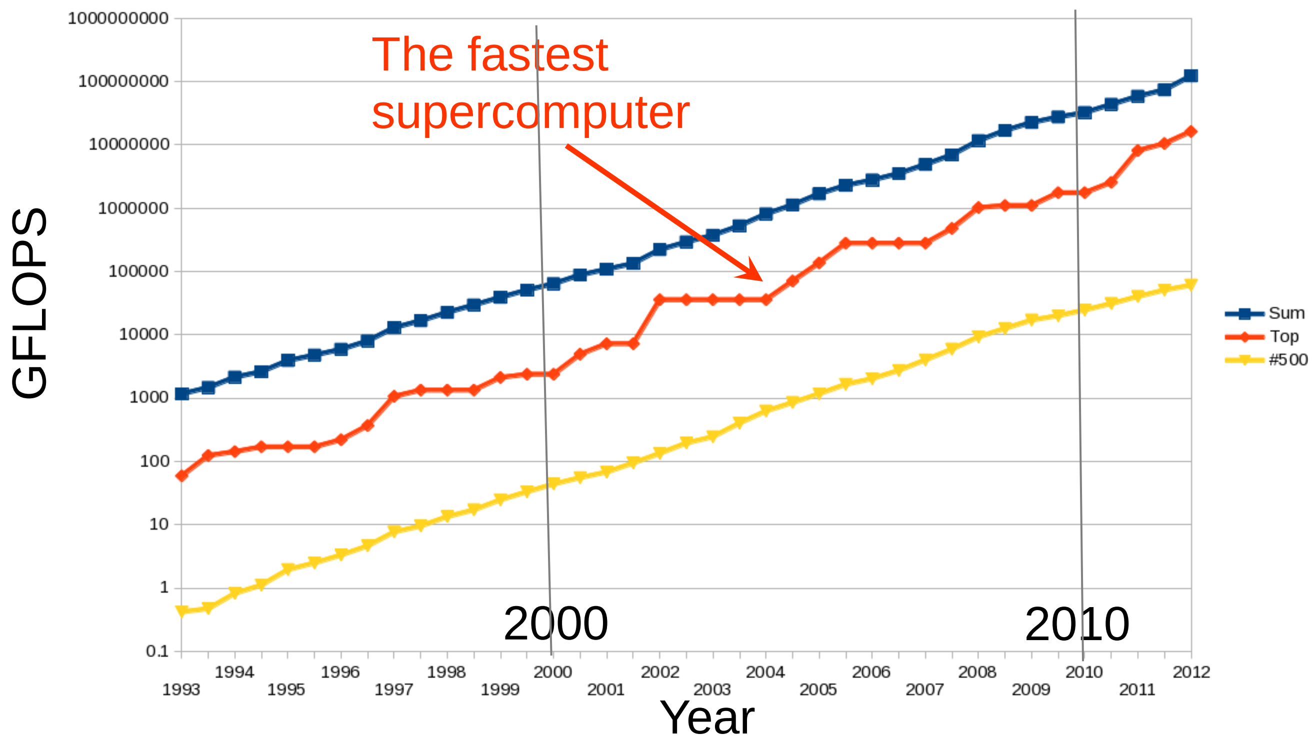
Outline

- Current status of model resolution for operational seasonal prediction
- Prospects from high-resolution modelling
  - Processes to be resolved / improved with high-resolution models
- Some efforts and approaches for high-resolution seasonal prediction
- Summary

Current status of model resolution for operational seasonal prediction

HITACHI SR16000 (JMA's HPC June 2012-)

Growth of supercomputers' performance



GPU-based & cluster HPCs increased.

Reducing horizontal grid spacing by a factor of 10 requires a factor of 10^3 increase of computational power.

Growth of supercomputers' performance, based on data from **top500.org** site (http://i.top500.org/). The *y*-axis shows performance in GFLOPS. The red line denotes the fastest supercomputer in the world at the time. From Wikipedia: http://en.wikipedia.org/wiki/TOP500.

Model resolution of CGCM (JMA)

2013? JMA/MRI-CGCM2

Atm: **T_L159** (~110 km, 1.125 deg.) L60 (~0.1hPa)

Ocn: **1**x1-0.3 L 53

2008 JMA/MRI-CGCM (2010- for Seasonal Fcst)

Atm: **T_L95** (~180 km, 1.875 deg.) L40 (~0.4hPa)

Ocn: **1**x1-0.3 (30N-30S) L51 (top: ~1m)

2003 JMA-CGCM02 (GSM0103) *

Atm: **T63** (~180 km, 1.875 deg.) L40 (~0.4hPa)

Ocn: **2.5**x2-0.5(10N-10S) L20 (top: ~10 m)

1999 JMA-CGCM01 (GSM8911) *

Atm: **T42** (~250 km) L21 (~10 hPa)

Ocn: **2.5**x2-0.5(10N-10S) L20

* CGCM for ENSO prediction

Model resolution of seasonal prediction (ECMWF)

2011 System 4 (IFS Cy36r4, NEMO)

Atm: **T_L255** (~80 km, 0.7 deg.) **L91** (~0.01hPa)

Ocn: **1**x1-0.3 deg. L42, 51M

2003 System 3 (IFS Cy31r1, HOPE)

Atm**: T_L159** (~125 km, 1.125 deg.) **L62** (~0.5hPa)

Ocn: **1.4**x1.4-0.3 deg. (30N-30S) L29 (top: ~10 m) , 41M

2001 System 2 (IFS Cy23r4, HOPE)

Atm: **T_L95** (~210 km, 1.875 deg.) **L40**

Ocn: **1.4**x1.4-0.3 deg. (30N-30S) L29 (top: ~10 m)

1997 System 1 (IFS Cy15r8, HOPE)

Atm: **T63** (~210 km) **L31**

Ocn: **2.8**x2.8-0.5 deg. (10N-10S) L20

Model resolution UK climate models

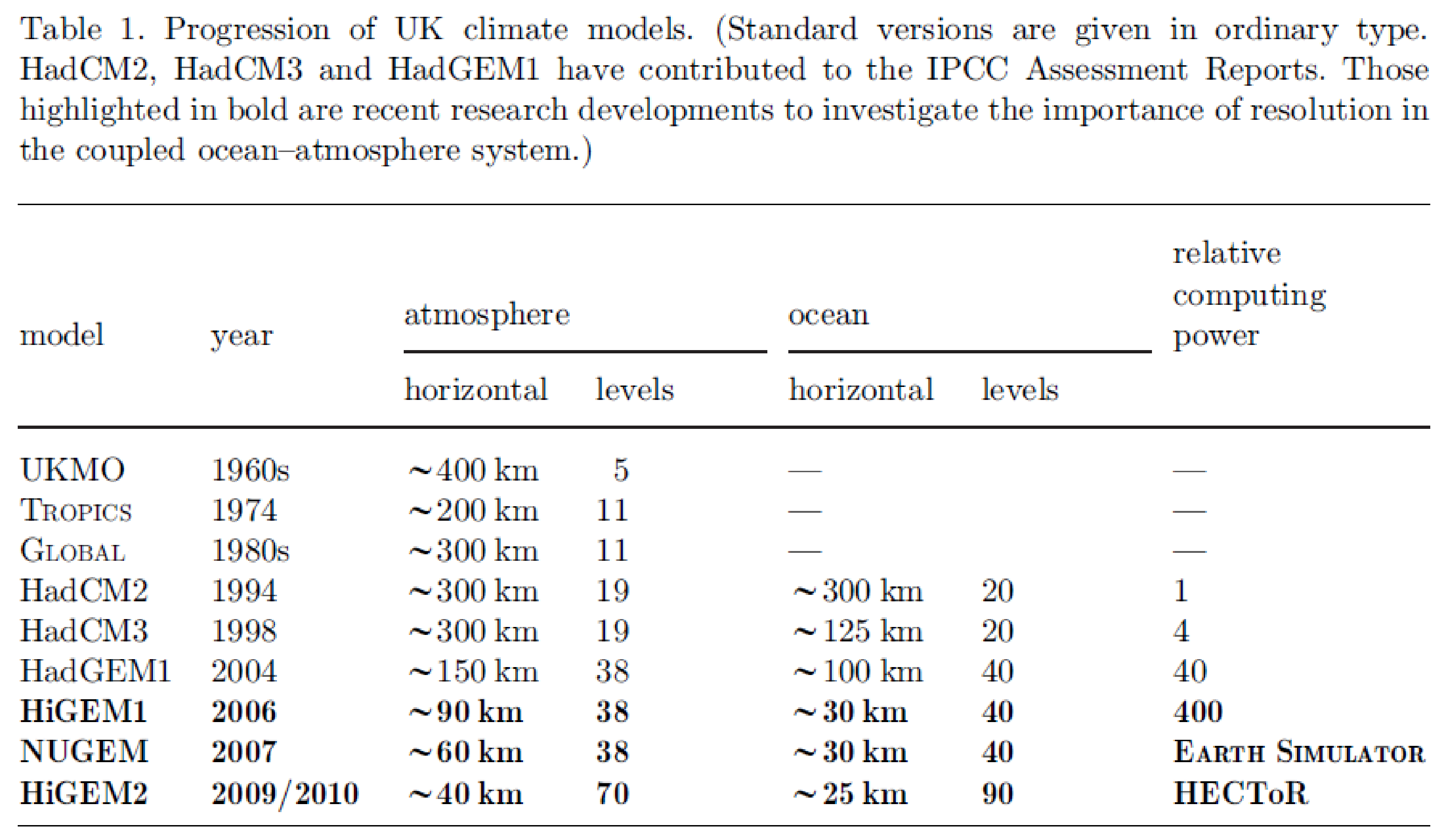


Table 1. Progression of UK climate models. (Standard versions are given in ordinary type. HadCM2, HadCM3 and HadGEM1 have contributed to the IPCC Assessment Reports. Those highlighted in bold are recent research developments to investigate the importance of resolution in the coupled ocean–atmosphere system.)

model	year	atmosphere		ocean		relative computing power
		horizontal	levels	horizontal	levels	
UKMO	1960s	~400 km	5	—		—
Tropics	1974	~200 km	11	—		—
Global	1980s	~300 km	11	—		—
HadCM2	1994	~300 km	19	~300 km	20	1
HadCM3	1998	~300 km	19	~125 km	20	4
HadGEM1	2004	~150 km	38	~100 km	40	40
HiGEM1	**2006**	**~90 km**	**38**	**~30 km**	**40**	**400**
NUGEM	**2007**	**~60 km**	**38**	**~30 km**	**40**	**Earth Simulator**
HiGEM2	**2009/2010**	**~40 km**	**70**	**~25 km**	**90**	**HECToR**

Slingo et al. 2009

What did hinder upgrades of resolution of seasonal prediction? (1)

- Seasonal prediction systems require a huge amount of re-forecasts (hindcasts) for verification and calibration.

- If we conduct a set of re-forecast: 15 members ensemble, 7 months integration, 12 cases per year, 30 years, then it requires…

30 yr x 12 cases x 15 mem x 7 mon

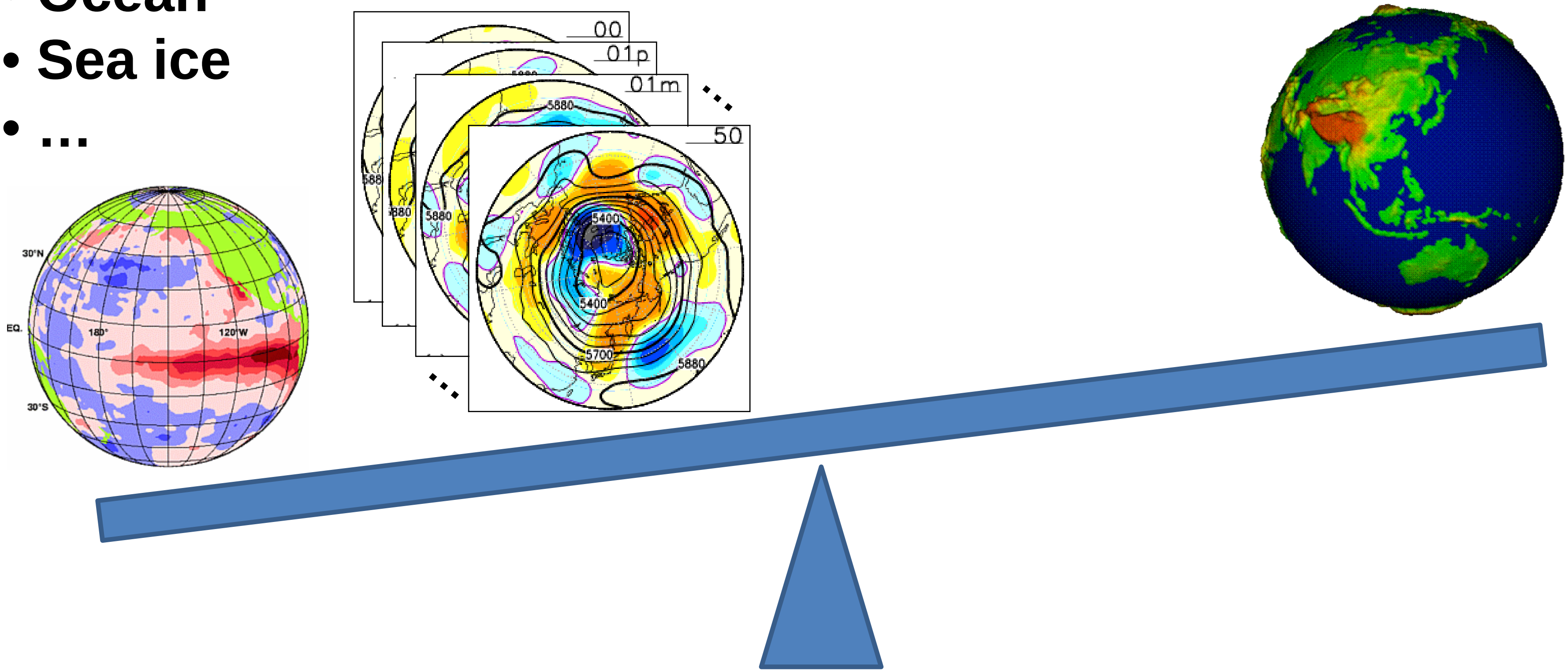
= 3150 years integration!

What did hinder upgrades of resolution of seasonal prediction? (2)

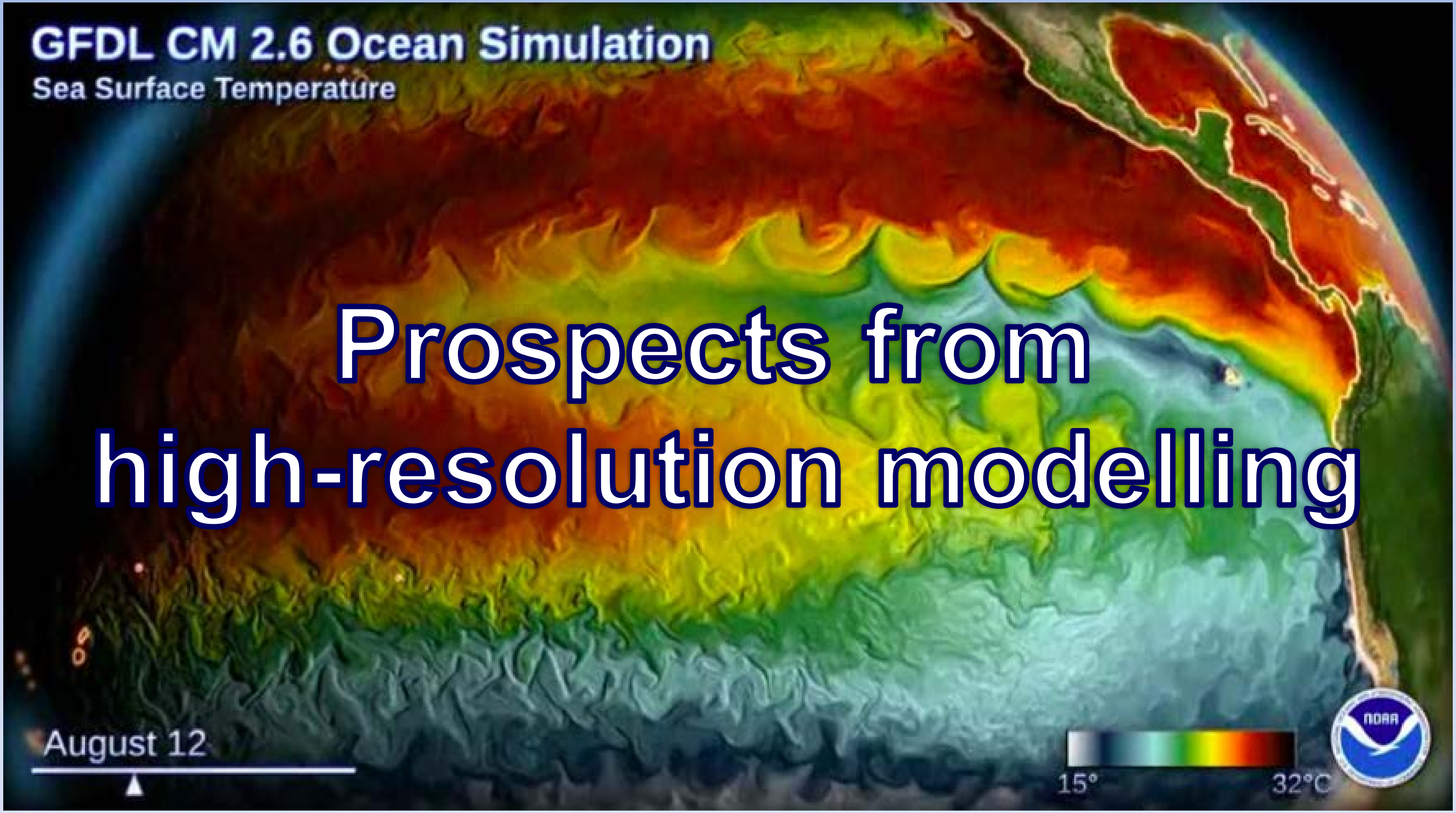
Additional Components
- **Ocean**
- **Sea ice**
- **…**

Ensemble size
Longer reforecast

High resolution



Prospects from high-resolution modelling



GFDL CM2.6 (0.1 deg. resolution ocean model) simulation

http://www.gfdl.noaa.gov/flash-video?vid=cm26_v5_sst&w=940

High-resolution coupled models

Model	Modelling Centre	Atm. Model/ Atm. Res.	Ocn. Model/ Ocn. Res.	Reference
CM2.4/CM2.5/CM2.6	GFDL	1/0.5/0.5° 100/50/50km	0.25/0.25/0.1° 25/25/10km	Delworth et al. (2012), JC
CCSM4	NCAR	CAM3.5 0.23° x0.31°	POP2 0.1°	McClean et al. (2011), OM
MIROC4h	CCSR/NIES/FRCGC	CCSR/NIES/FRCGC AGCM v5.7 T213 ~0.5°	COCO v3.4 0.28125x0.1875	Sakamoto et al. (2012), JMSJ
HiGEM	UKMO HC/ NERC	HadGEM1 N144 1° ~90 km	NEMO 1/3°	Shaffrey et al. (2009), JC
CFES	ESC JAMSTEC	AFES 50km T239	OFES 0.25°	Komori et al. (2008), GRL

High resolution makes a difference? What processes?

- **Ocean**
  - Western Boundary Current, Ocean Fronts
  - Tropical Instability Wave (TIW)
  - Meso-scale Eddies
  - Atlantic Meridional Overturning Circulation (AMOC)
  - ENSO
- **Atmosphere**
  - Sub-synoptic Eddies
  - Blocking
  - Tropical & Extratropical Cyclones
  - Precipitation Intensity
  - Stratosphere-troposphere Interaction

Bryan et al. 2010
Delworth et al. 2012
Roberts et al. 2009
Shaffrey et al. 2009
Sakamoto et al. 2012
Kirtman et al. 2012
in press
…

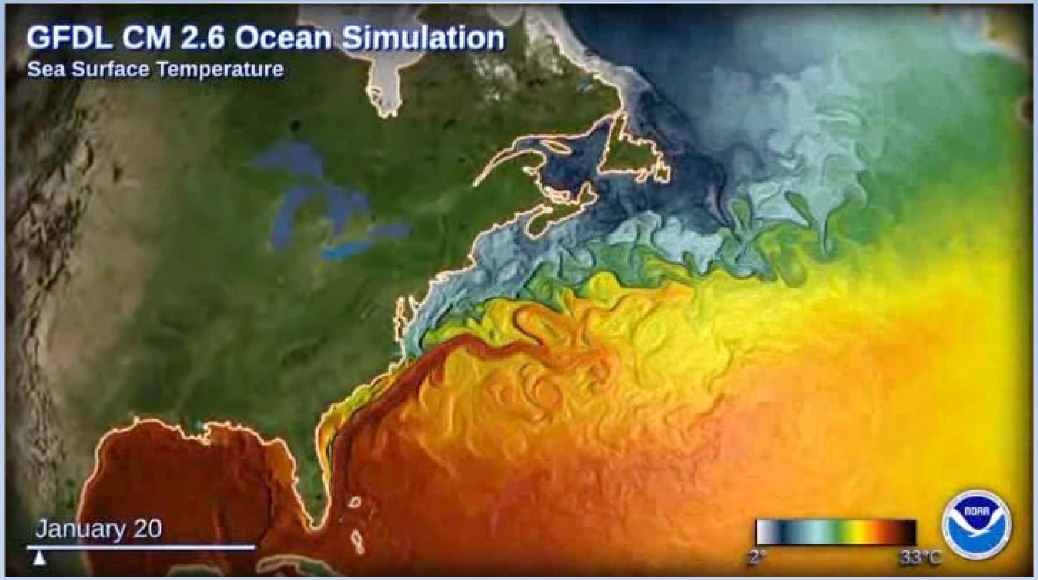
Increase of Ocean Model Resolution

Eddy-resolving-resolution ocean models drastically improve its performance in reproducing fine scale variabilities (meso-scale eddies, WBC, TIW) compared to **non-eddy-permitting-resolution**.

- **Non-eddy-permitting resolution (~1 deg.)**
  - The eddy effect (such as mixing) is parameterized (e.g., Gent and McWilliams 1990).
- **Eddy-permitting resolution (~0.25 deg.)**
  - Ocean eddies are partly represented.
- **Eddy-resolving resolution (~ 0.1 deg.)**
  - Ocean eddies are resolved.
  - Mixing and transports due to eddies are resolved, reproducing mean climate satisfactorily.

Bryan (2007) Ocean Modelling

GFDL CM 2.6 simulation



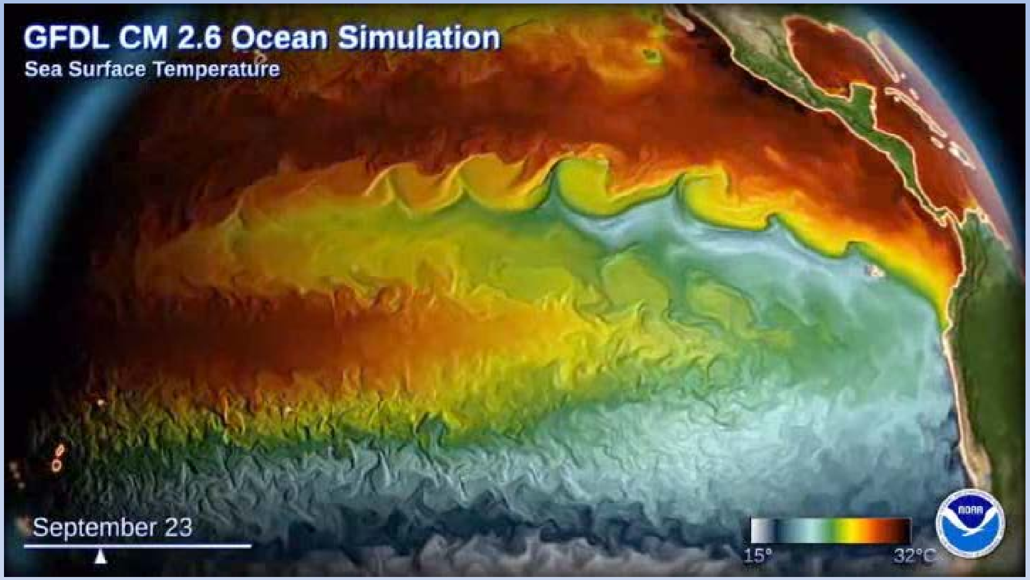
Gulf Stream

- 100-200 km width
- One of the strongest current (western boundary current)

From GFDL/NOAA web site

http://www.gfdl.noaa.gov/flash-video?vid=cm26_v5_sst&w=940

GFDL CM 2.6 simulation



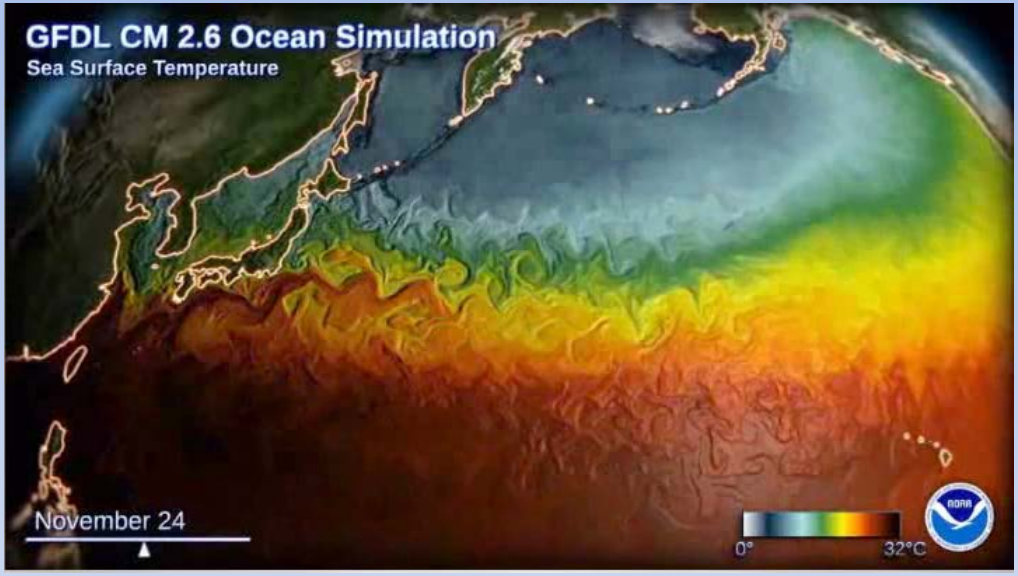
Tropical Instability Wave (TIW)

- **Cusp-shaped instability wave just north of the equator in both the Pacific and Atlantic oceans**
- **1000 - 2000 km, 20-40 days period**
- **Influence on ENSO variablity**

From GFDL/NOAA web site

http://www.gfdl.noaa.gov/flash-video?vid=cm26_v5_sst&w=940

GFDL CM 2.6 simulation



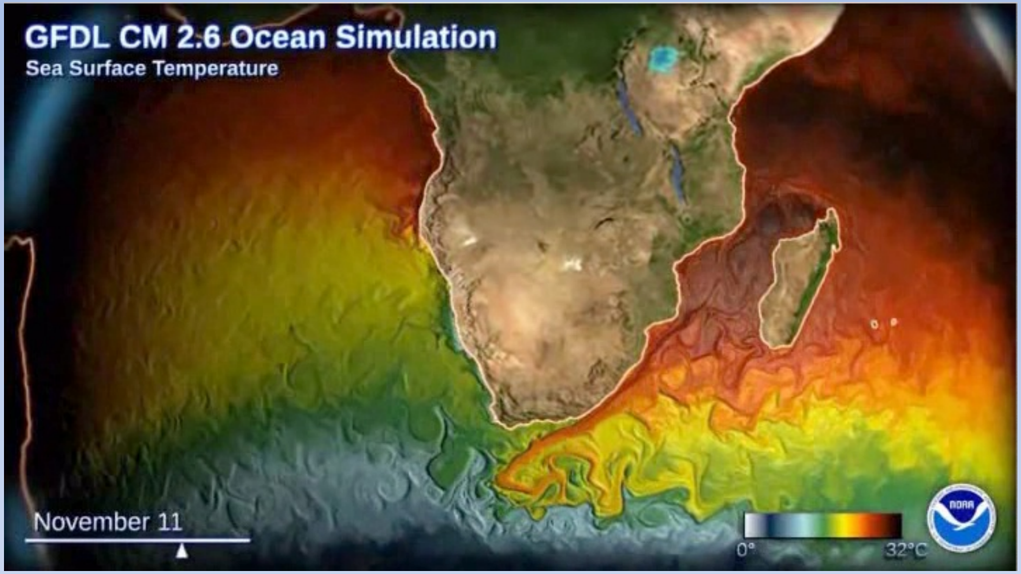
Kuroshio current

- 100 km width
- some times exceeds 2 m/s

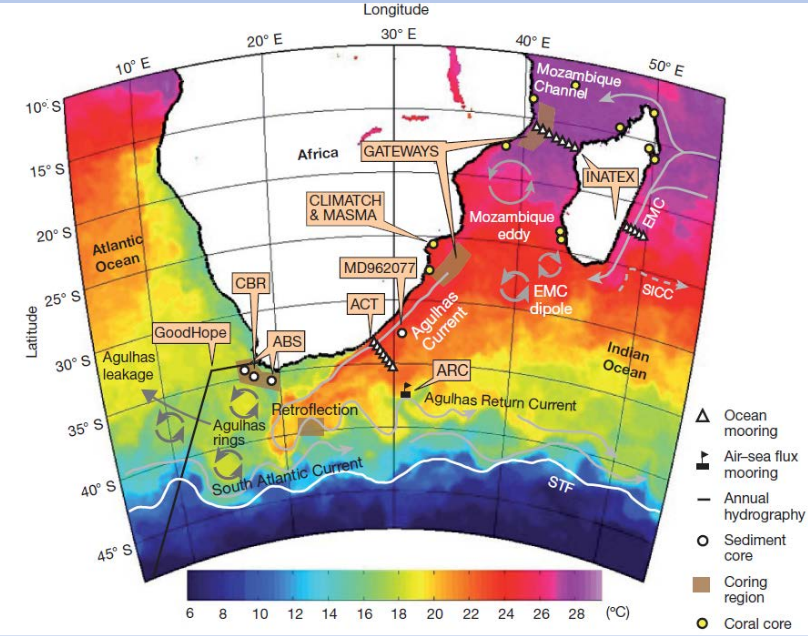
From GFDL/NOAA web site

http://www.gfdl.noaa.gov/flash-video?vid=cm26_v5_sst&w=940

GFDL CM 2.6 simulation



Agulhas system



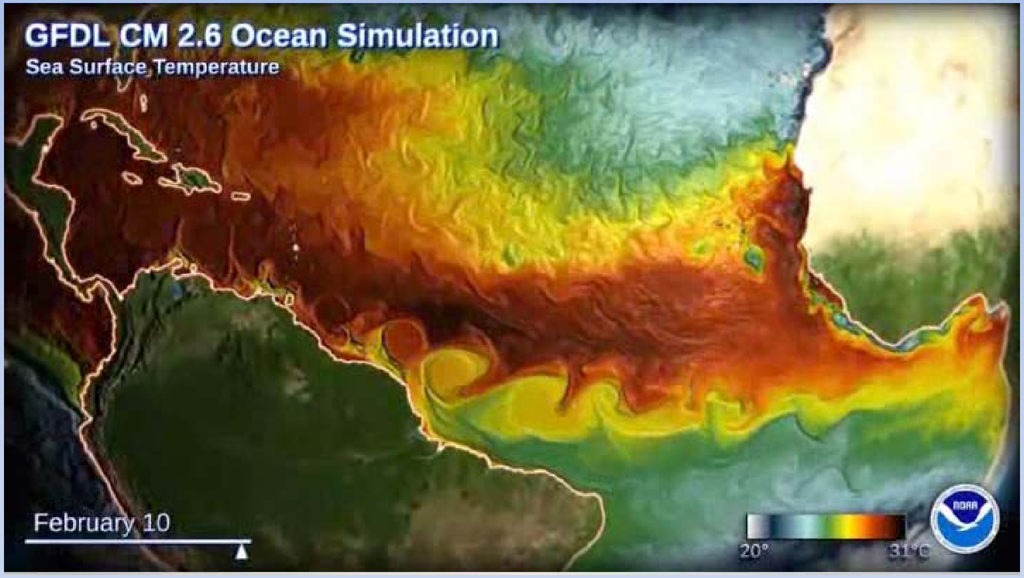
- Agulhas Current
- Agulhas Counter Current
- Agulhas leakage, Rings -> AMOC

cf. Beal et al. (2011) Nature

From GFDL/NOAA web site

http://www.gfdl.noaa.gov/flash-video?vid=cm26_v5_sst&w=940

GFDL CM 2.6 simulation



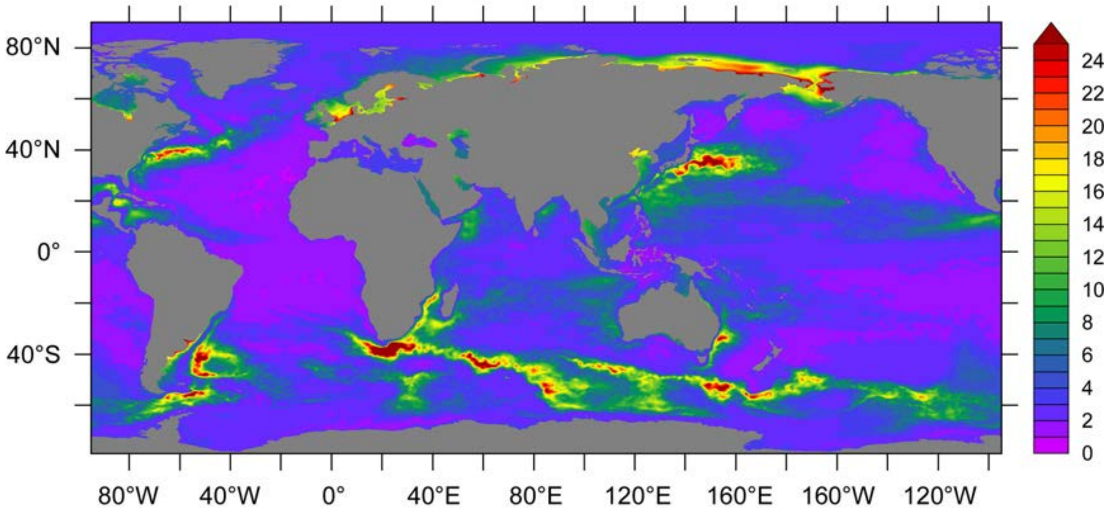
TIW in the Atlantic Ocean

From GFDL/NOAA web site

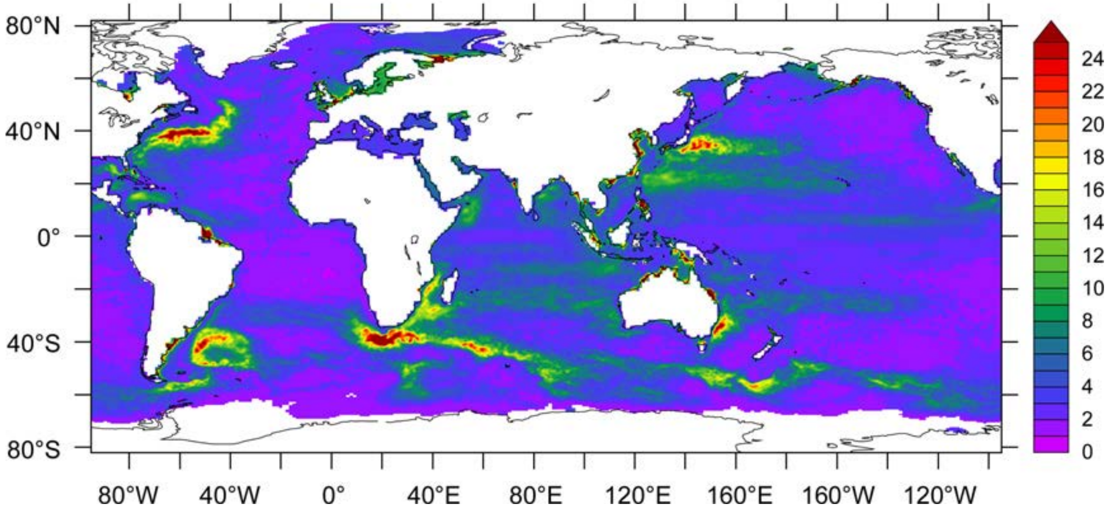
http://www.gfdl.noaa.gov/flash-video?vid=cm26_v5_sst&w=940

Ocean variability（meso-scale eddies） in high res. CGCM

(a) CCSM4 Mesoscale RMS SSHA (cm)



(b) T/P & ERS Mesoscale RMS SSHA (cm)



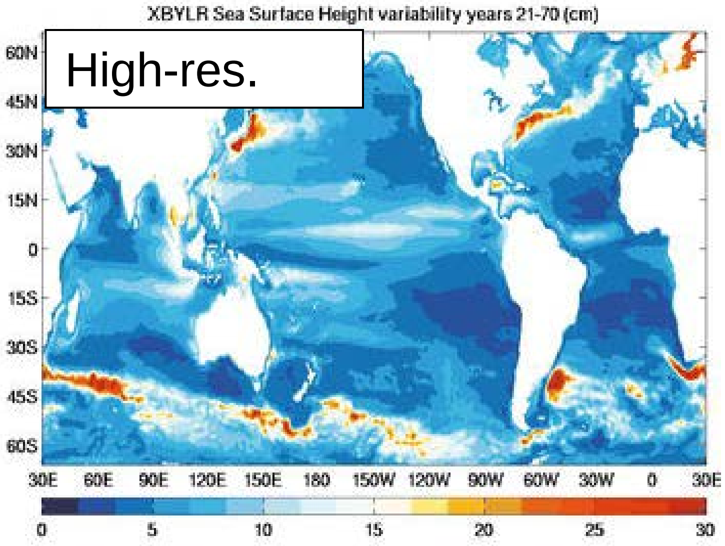
Mesoscale RMS SSHA (cm) from (a) the ocean component of CCSM4 for years 15–19 and (b) the AVISO-blended (TOPEX/POSEIDON and ERS 1 and 2) altimetry for 1997–2001.

CCSM4 simulation
Ocean, ice: 0.1 deg.
Atmosphere: 0.25 deg.

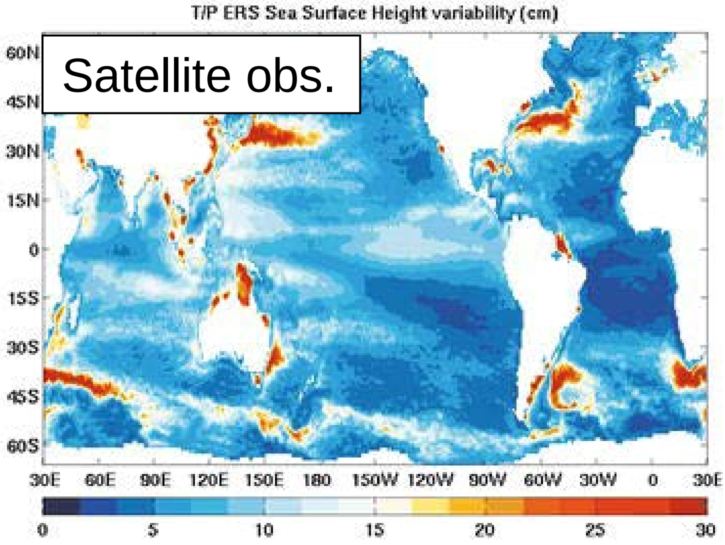
McClean et al. 2011
Ocean Modelling

Ocean variability（meso-scale eddies）in high res. CGCM

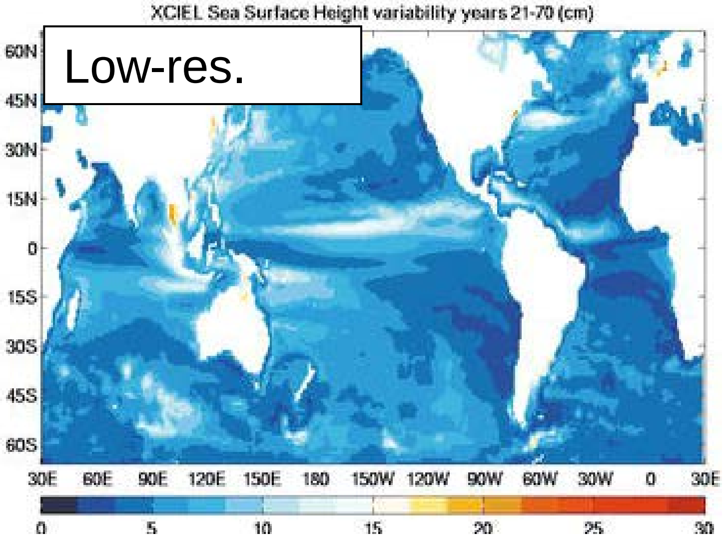
b)


XBYLR Sea Surface Height variability years 21-70 (cm)

a)


T/P ERS Sea Surface Height variability (cm)

c)


XCIEL Sea Surface Height variability years 21-70 (cm)

HadGEM1

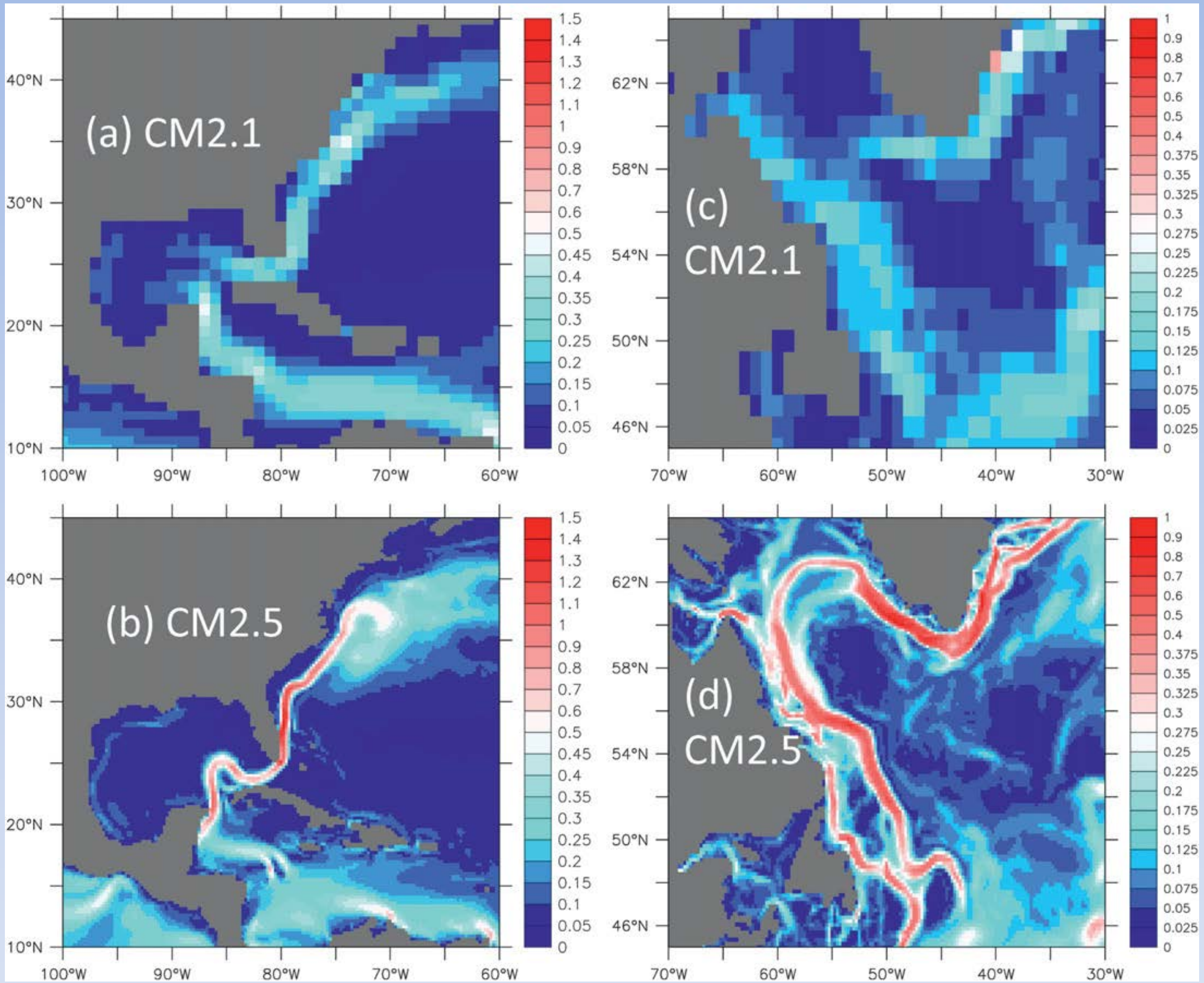
Atm: 1.25 x 1.875 deg. (N96), L38 39km
Ocn: 1 x 1 deg (increasing to 1/3 deg. Meridionally near the equator), L40

HiGEM

Atm: 0.83 x 1.25 deg. (N144) ~90 km , L38. 39km
Ocn: 1/3 x 1/3 deg., L40

Shaffrey et al. 2009

Western Boundary Current

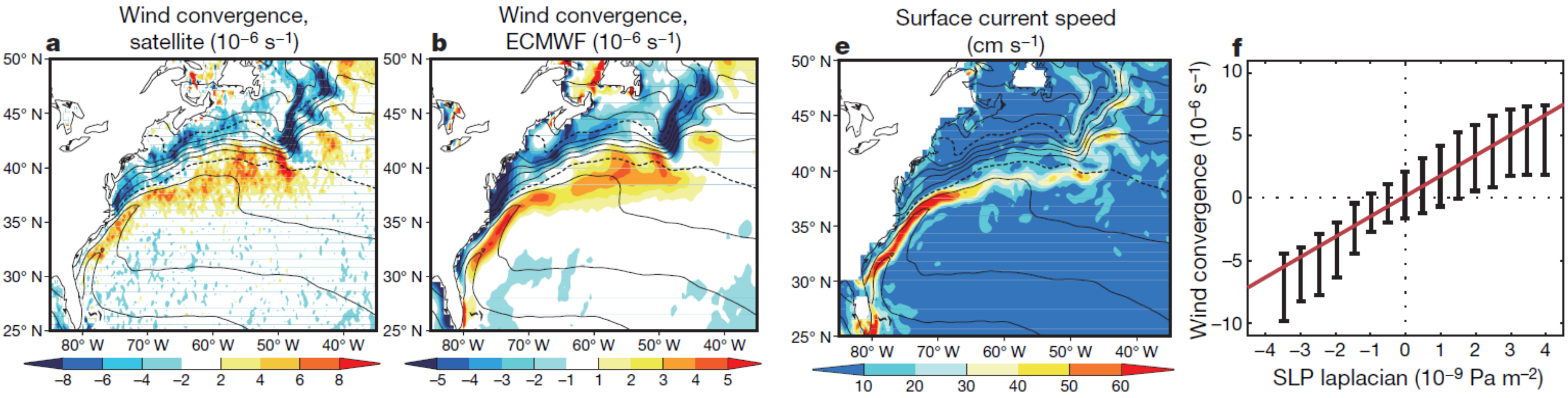


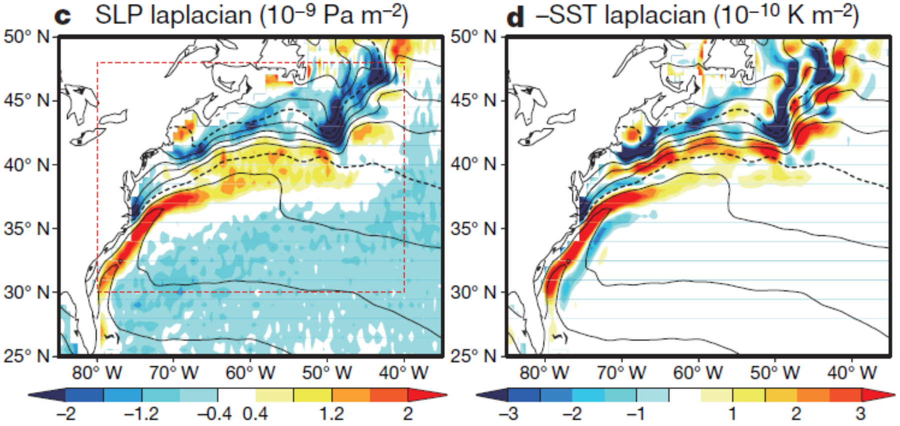
Annual mean surface current speed (m s^{-1}). Gulf Stream region for (a) CM2.1 and (b) CM2.5. Labrador Sea region for (c) CM2.1 and (d) CM2.5.
All values plotted are annual mean averages over the period of years 101–200 of the 1990 control runs.

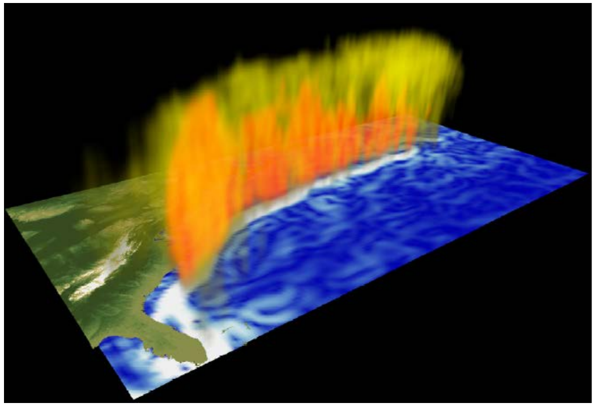
CM2.1 atm: 200 km, ocn: 100km
CM2.5 atm: 50 km, ocn: 28km

Delworth et al. 2012

Extratropical air-sea interaction over sharp meridional SST gradients (1)







Minobe et al. 2008 Nature

Extratropical air-sea interaction over sharp meridional SST gradients (2)

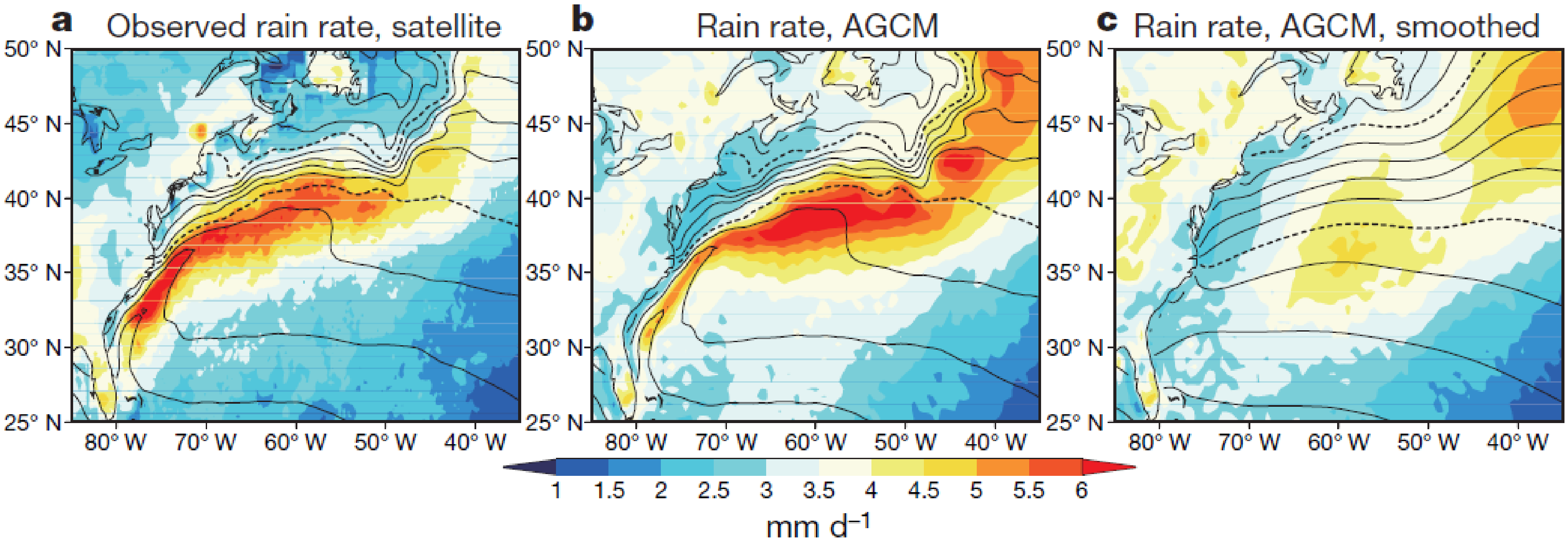
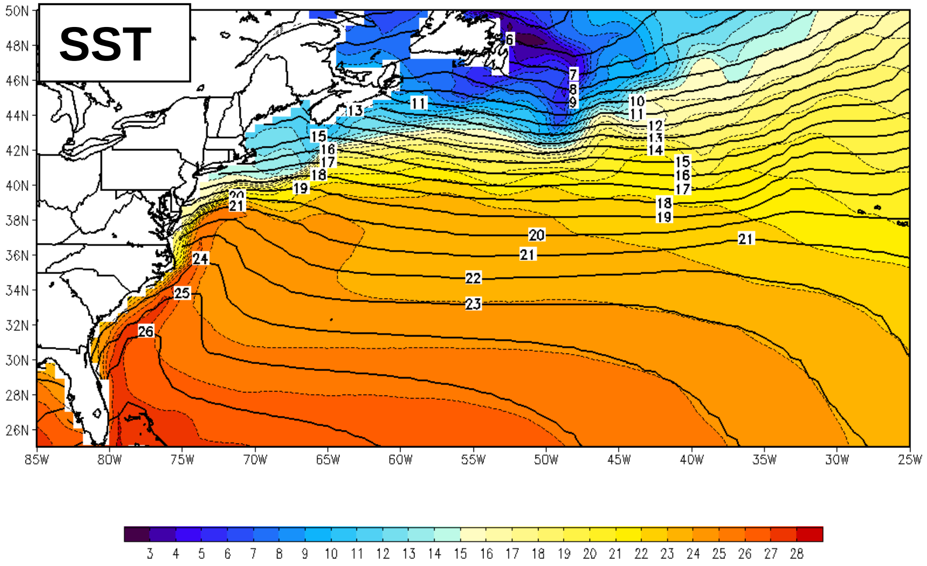
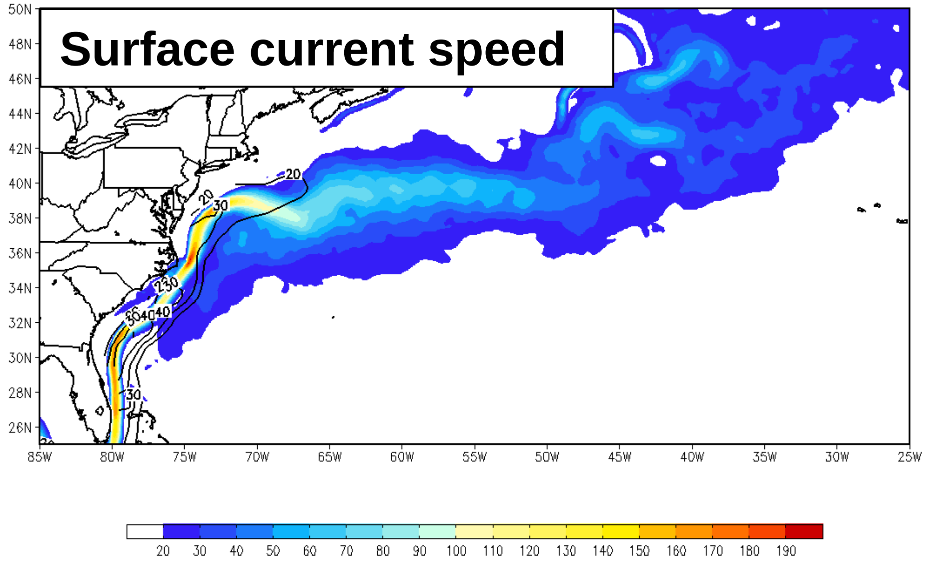


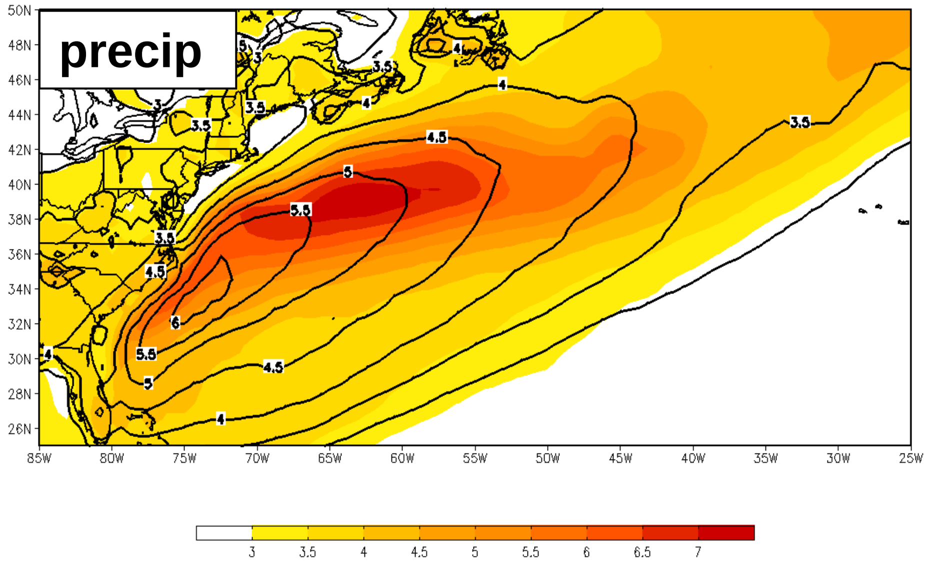
Figure 2 | Annual climatology of rain rate. **a**, Observed by satellites. **b**, **c**, In the AGCM with observed (**b**) and smoothed (**c**) SSTs. Contours are for SST, as in Fig. 1.

Minobe et al. 2008

Improvements in High-res. CCSM simulation







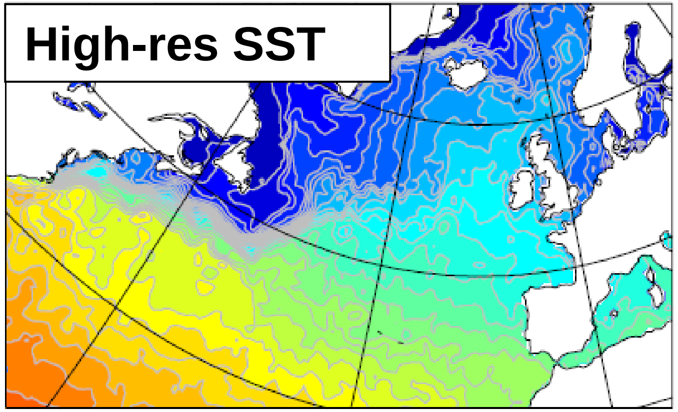
Simulated annual mean fields with CCSM model, colours (eddy-resolving ocean), contours (non-eddy-resolving ocean).

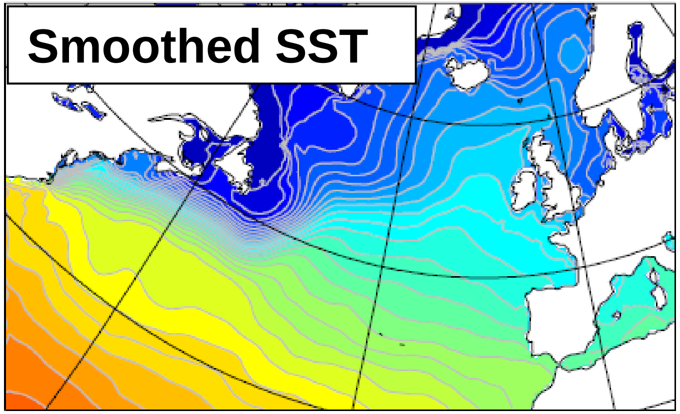
Atm. res.: 0.5 deg.
Ocean res.: 1.2 (low) and 0.1 (high) deg.

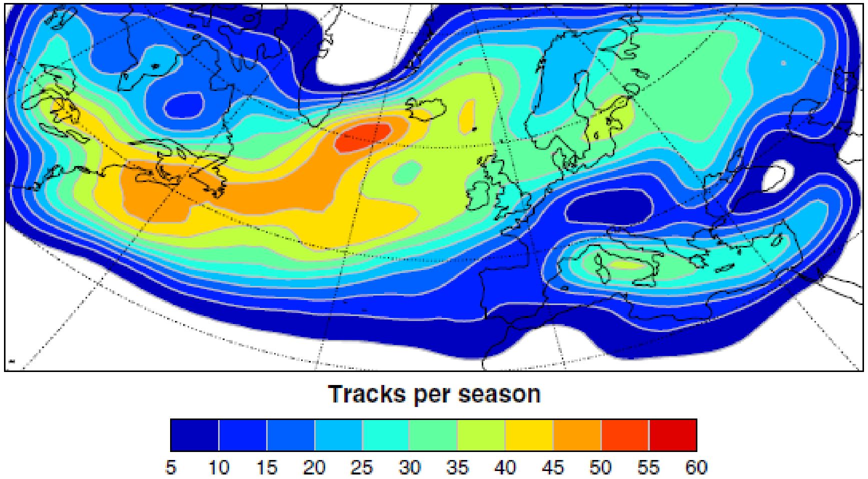
Kirtman et al. 2012 CD in press

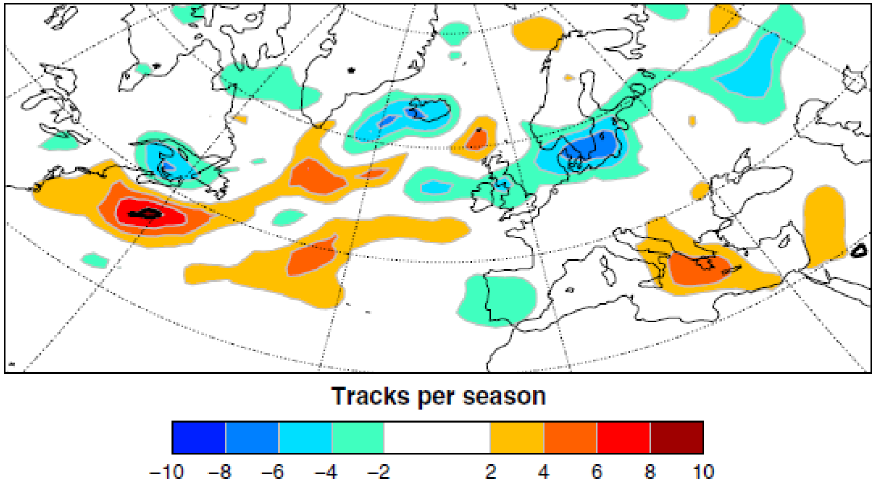
Ocean fronts and storm track (1)

Model: HadRAM3p
Grid size: 0.44 deg. (~50 km)
SST: Reynolds et al. (2007)
Period: Jan. 1985 – Nov. 2000


High-res SST


Smoothed SST

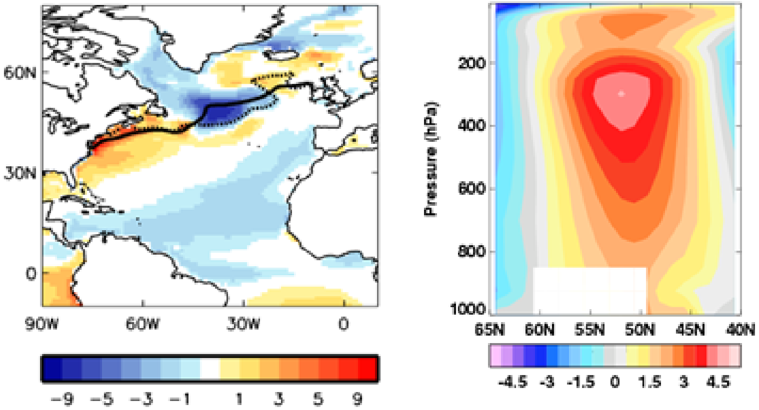

850hPa Vorticity Track Density: HI–RES (DJF 85/86 – 99/00)


HI–RES – LOW–RES

Woollings et al. 2011 Clim. Dyn.

Ocean Biases and Blocking Errors

Current Model (1 deg, ocean)

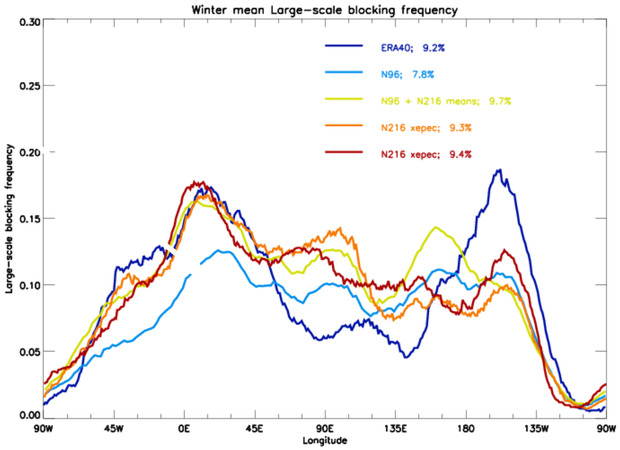


Gulf Stream Bias

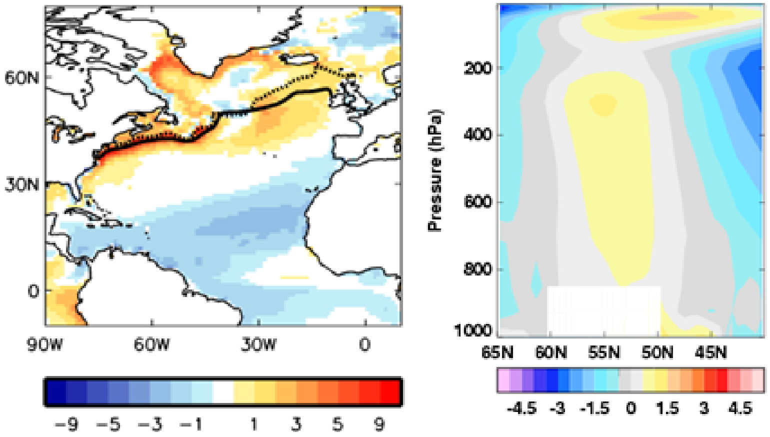
Wly wind bias

=> Blocking Deficit

Blocking Frequency



New Model (0.25 deg, ocean)



No Gulf Stream Bias

No Wly wind bias

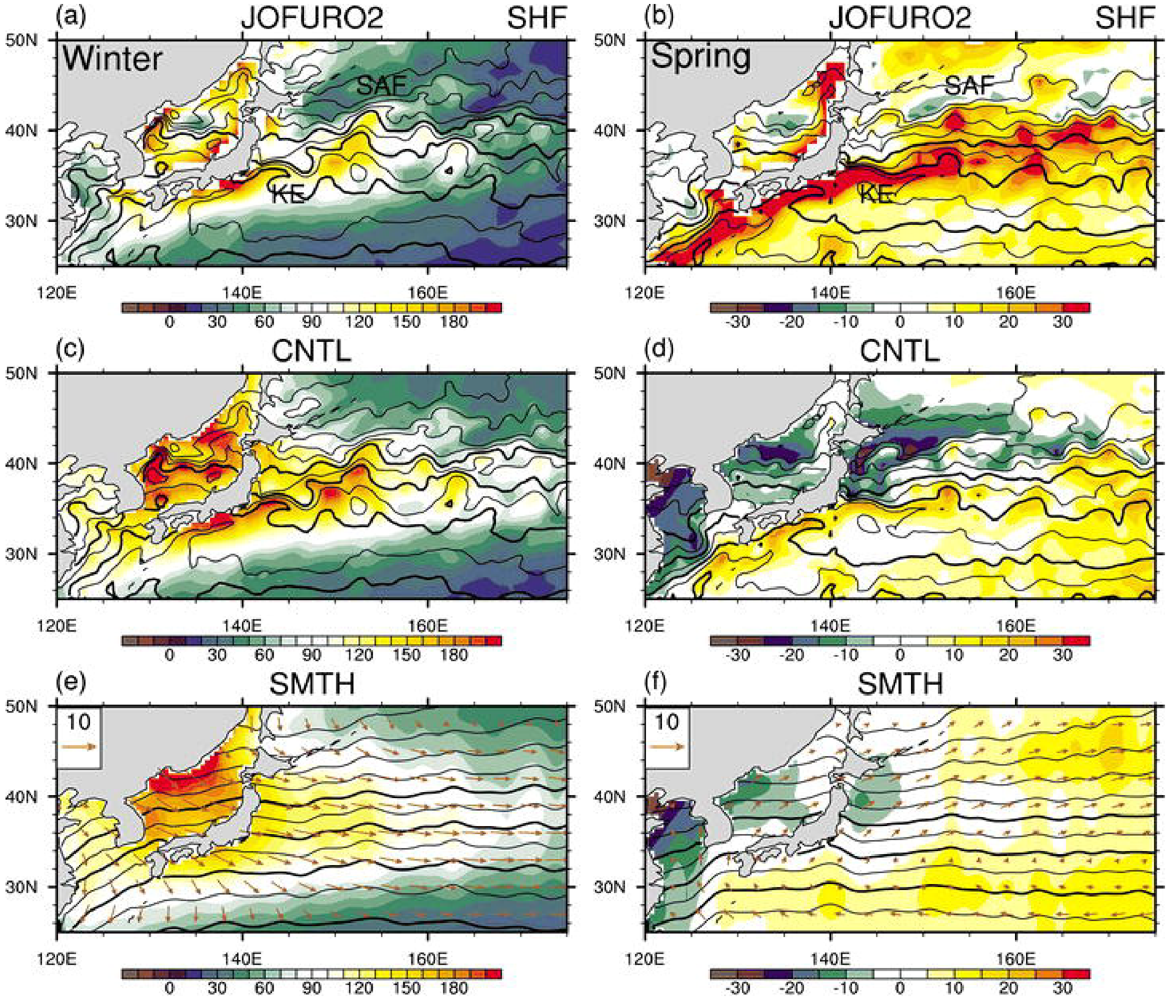
=> Good Blocking

Courtesy Adam Scaife

Scaife et al., *GRL*, 2011

Ocean fronts and storm track (2)

SST (contours), sensible heat flux (colors)



Atmospheric regional model experiments

Res.: 0.5 x 0.5 deg.

SST:
(CNTL) AMSR-E SST 0.25 deg.

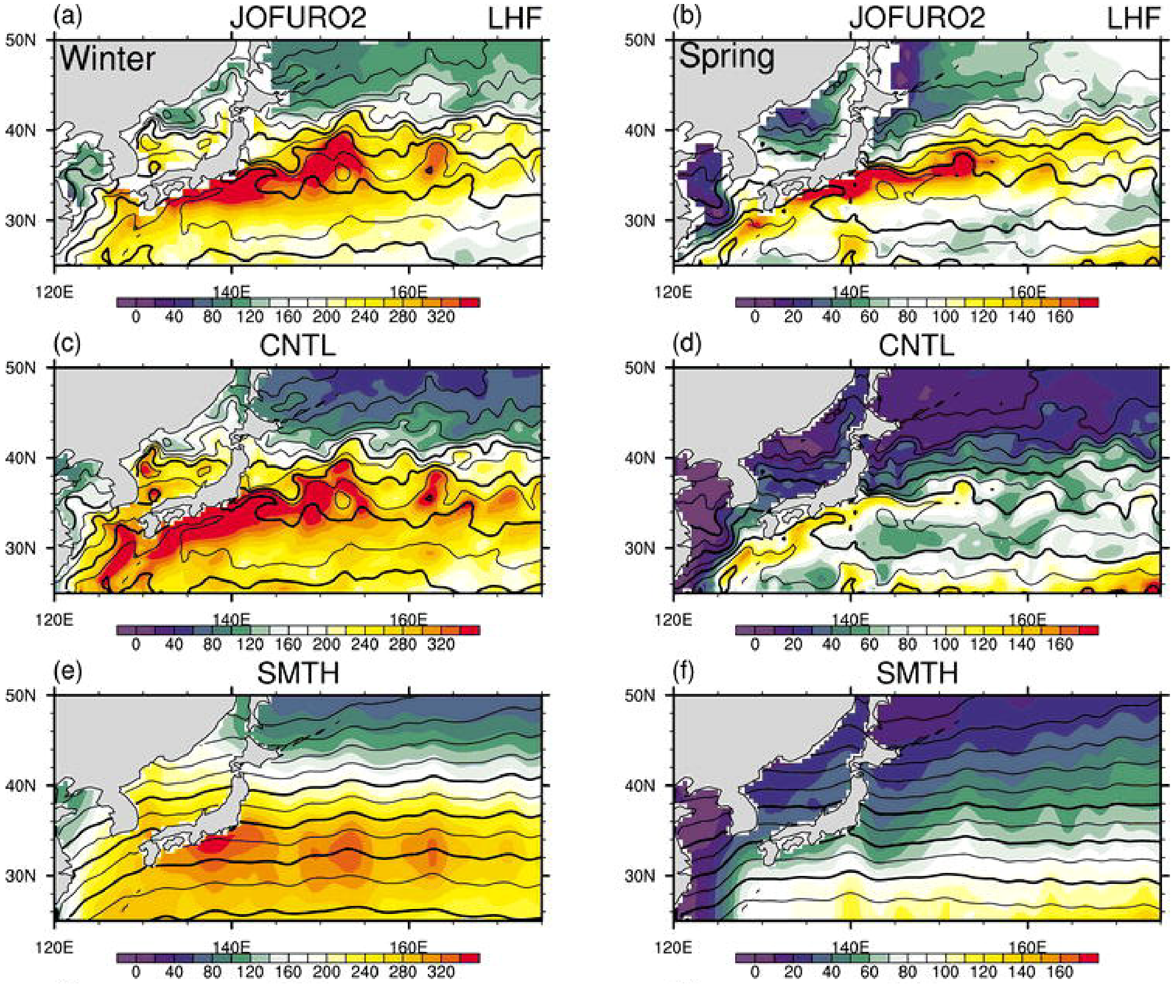
(SMTH) 10 deg. running mean smoothing in latitudinal direction

Taguchi et al. 2009

cf.) Inatsu et al. 2002, Brayshaw et al. 2008, Nakamura et al. 2008, Woolling et al. 2010 etc.

Ocean fronts and storm track (3)

SST (contours), latent heat flux (colors)



Atmospheric regional model experiments

Res.: 0.5 x 0.5 deg.

SST:
(CNTL) AMSR-E SST 0.25 deg.

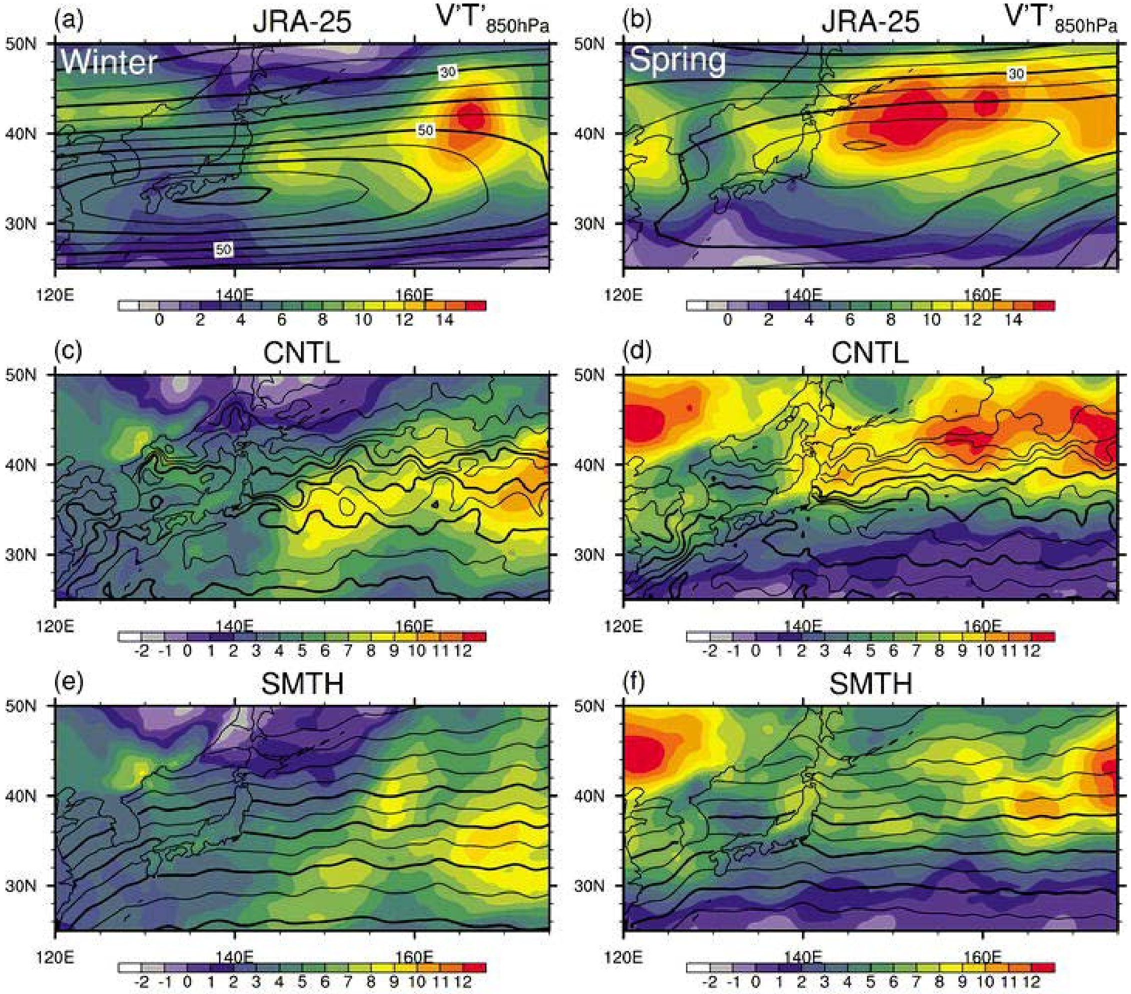
(SMTH) 10 deg. running mean smoothing in latitudinal direction

Taguchi et al. 2009

cf.) Inatsu et al. 2002, Brayshaw et al. 2008, Nakamura et al. 2008, Woolling et al. 2010 etc.

Ocean fronts and storm track (2)

SST (contours), 850-hPa poleward eddy heat flux $\overline{v'T'}$ (colors)

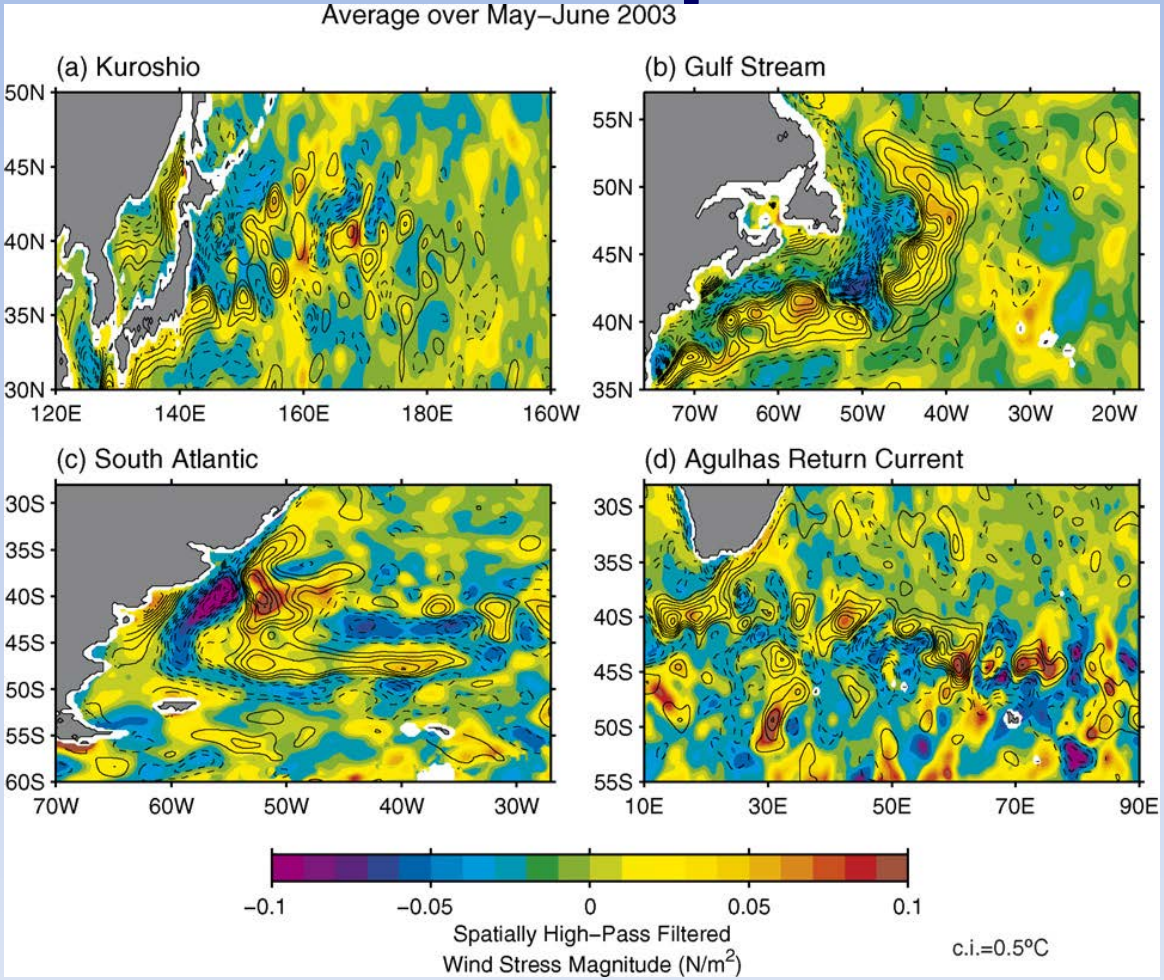


850-hPa eddy heat flux associated with transient eddies (Lanczos high-pass filter, cutoff: 8day) as a measure of their baroclinic growth.

Taguchi et al. 2009

cf.) Inatsu et al. 2002, Brayshaw et al. 2008, Nakamura et al. 2008, Woolling et al. 2010 etc.

Oceanic meso-scale eddies and atmosphere interaction



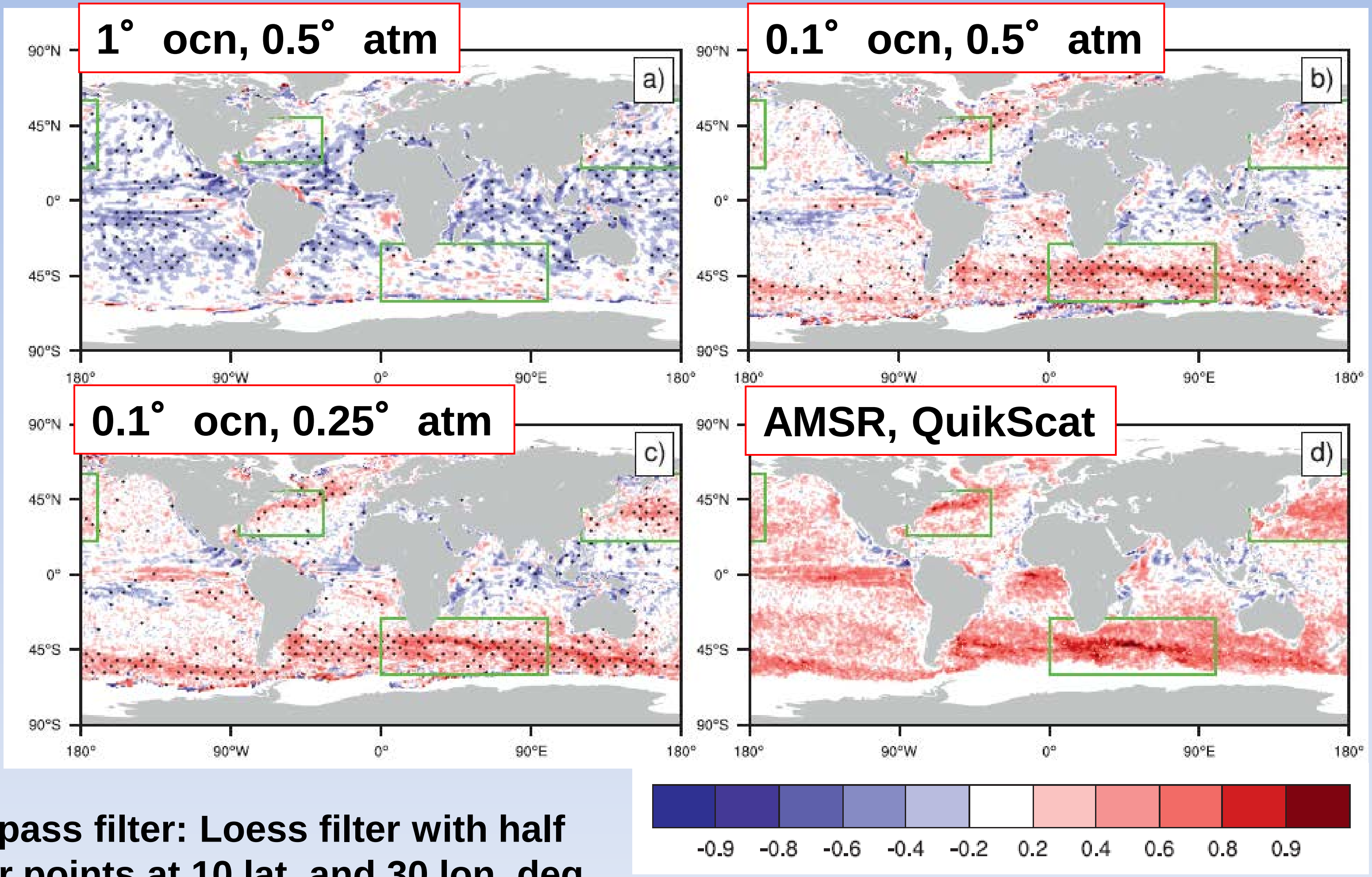
Maps of spatially high-pass filtered 2 months (May–June 2003) average wind stress magnitude (Nm^{-2}, color) and SST(°C, contours, interval 0.5 °C, zero contour omitted). Data from QuikSCAT scatterometer and AMSR-E.

(a) North-west Pacific, Kuroshio region (b) North-west Atlantic, Gulf Stream and North Atlantic Current region, (c) South-west Atlantic, Brazil-Malvinas confluence, and (d) Southern Indian Ocean, Agulhas Return Current.

Small et al. 2008

cf. Chelton et al. 2004

Temporal correlation of high-pass filtered surface wind speed with SST



1° ocn, 0.5° atm

0.1° ocn, 0.5° atm

0.1° ocn, 0.25° atm

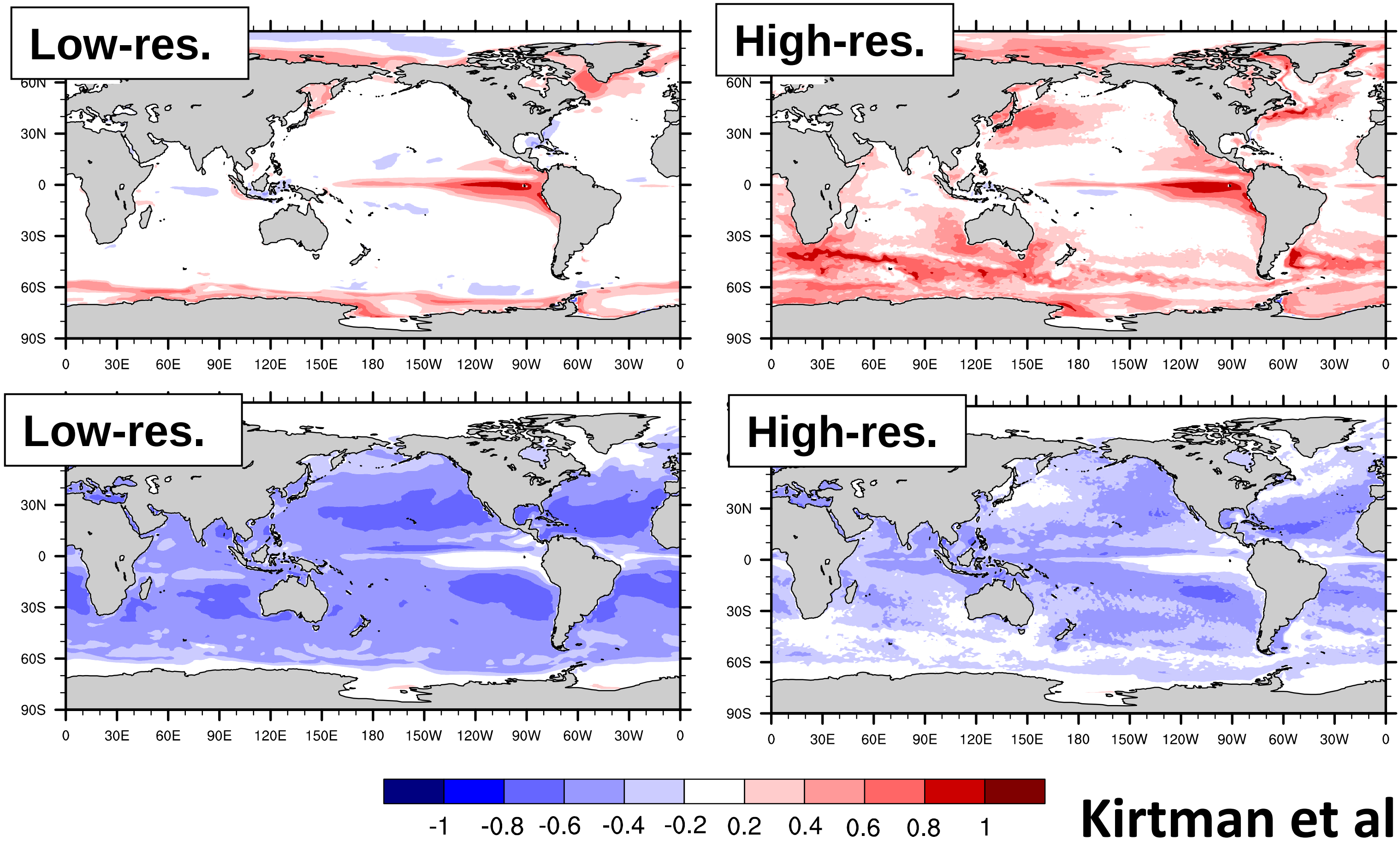
AMSR, QuikScat

High-pass filter: Loess filter with half power points at 10 lat. and 30 lon. deg.

Bryan et al. 2010 JC

Air-Sea interaction in High- & Low-res. ocean coupled models (CCSM)

Simultaneous pointwise correlations between turbulent heat flux (sensible +latent, positive upward) and SST (upper), and between turbulent heat flux and SST tendency (lower).



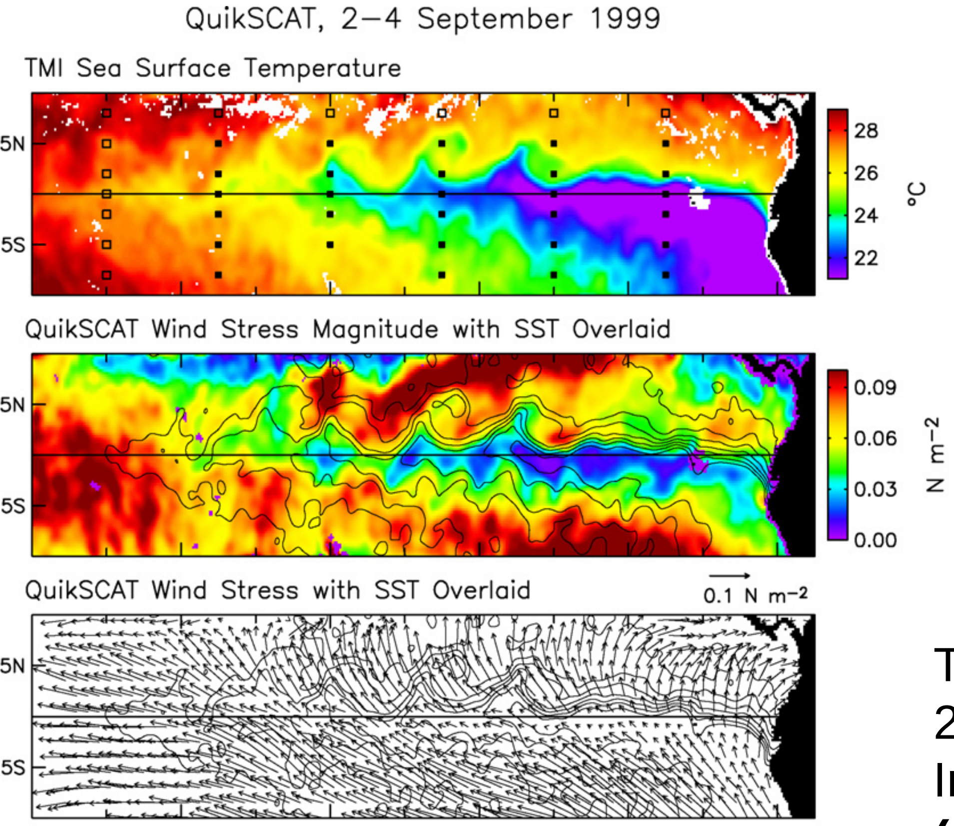
CCSM

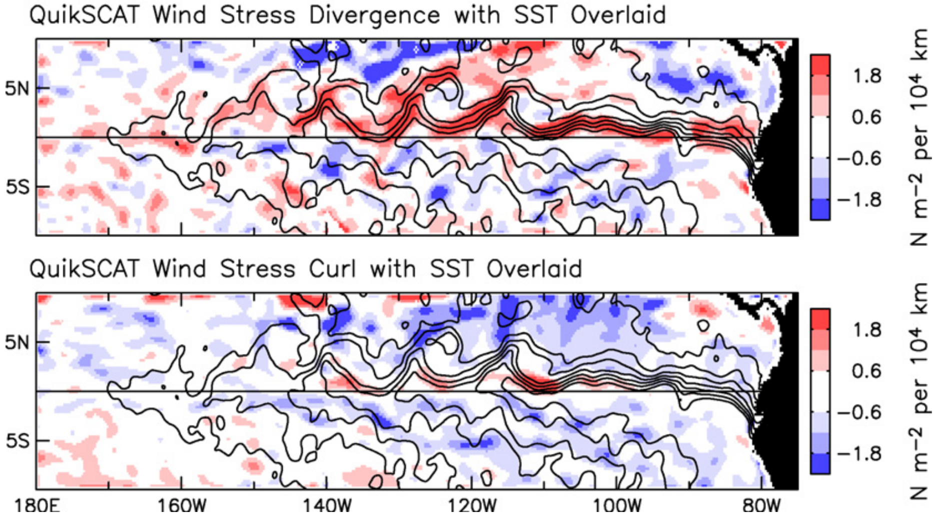
Low-res:
Atm: 0.5
Ocn:
1.2x0.54-0.27

High-res:
Atm:0.5
Ocn:0.1

Kirtman et al. 2012 in press

Air-sea interaction of TIW





Three-day average maps over the period 2–4 September 1999 showing Tropical Instability Waves.

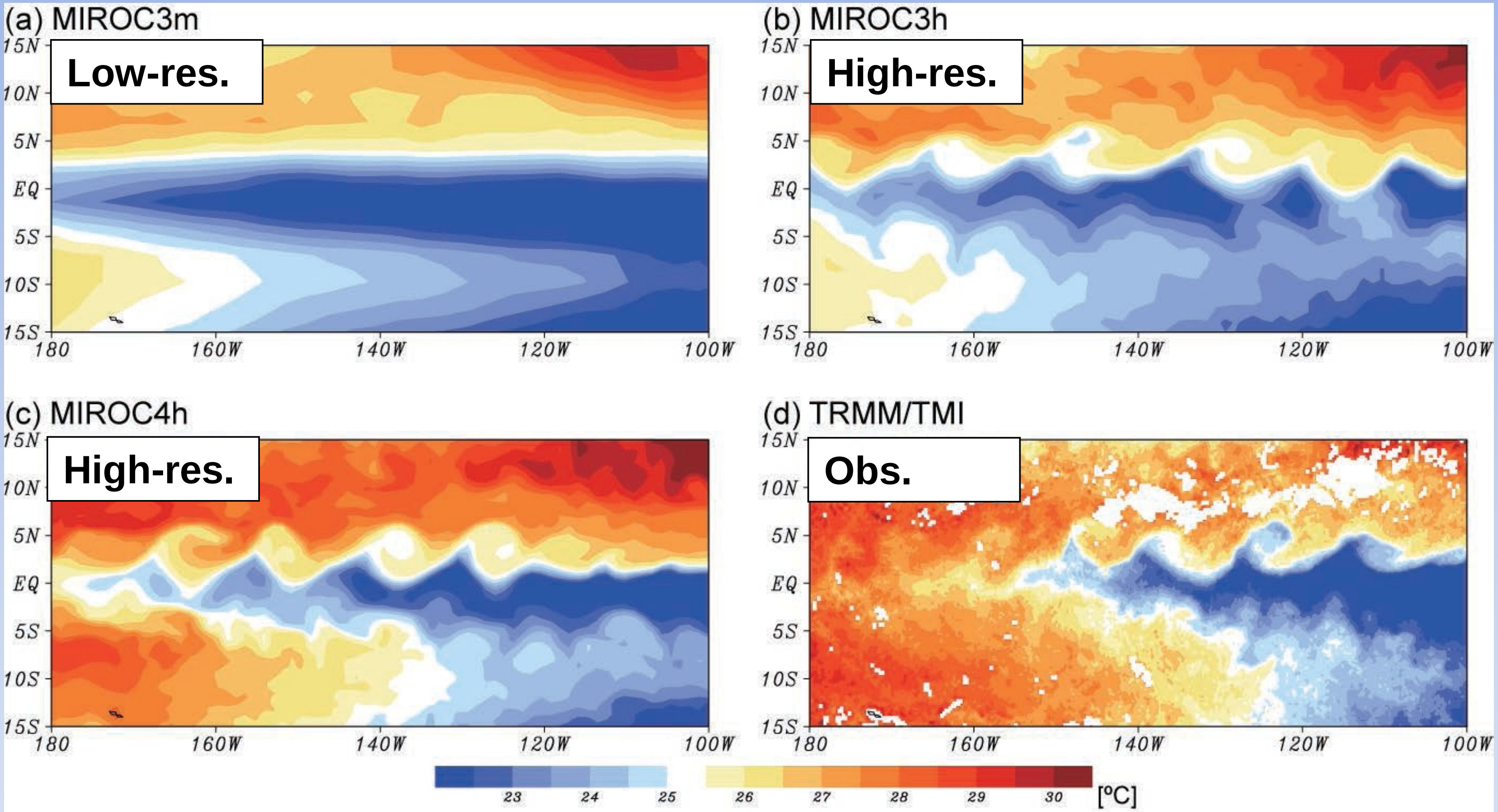
(top left) Sea surface temperature
(middle left) wind stress magnitude;
(bottom left) wind stress;
(top right) wind stress divergence;
(bottom right) wind stress curl.

Chelton et al. 2001

Obs: Xie et al. 1998 Chelton et al. 2001,

Model: Seo et al. 2007

ENSO and TIW



MIROC3m: atm 2.8deg., ocn 1.4x0.56-1.4 deg.
MIROC3h: atm: 1.125 deg, ocn:0.28125x0.1875
MIROC4h: atm. 0.5625 deg. ocn:0.28125x0.1875

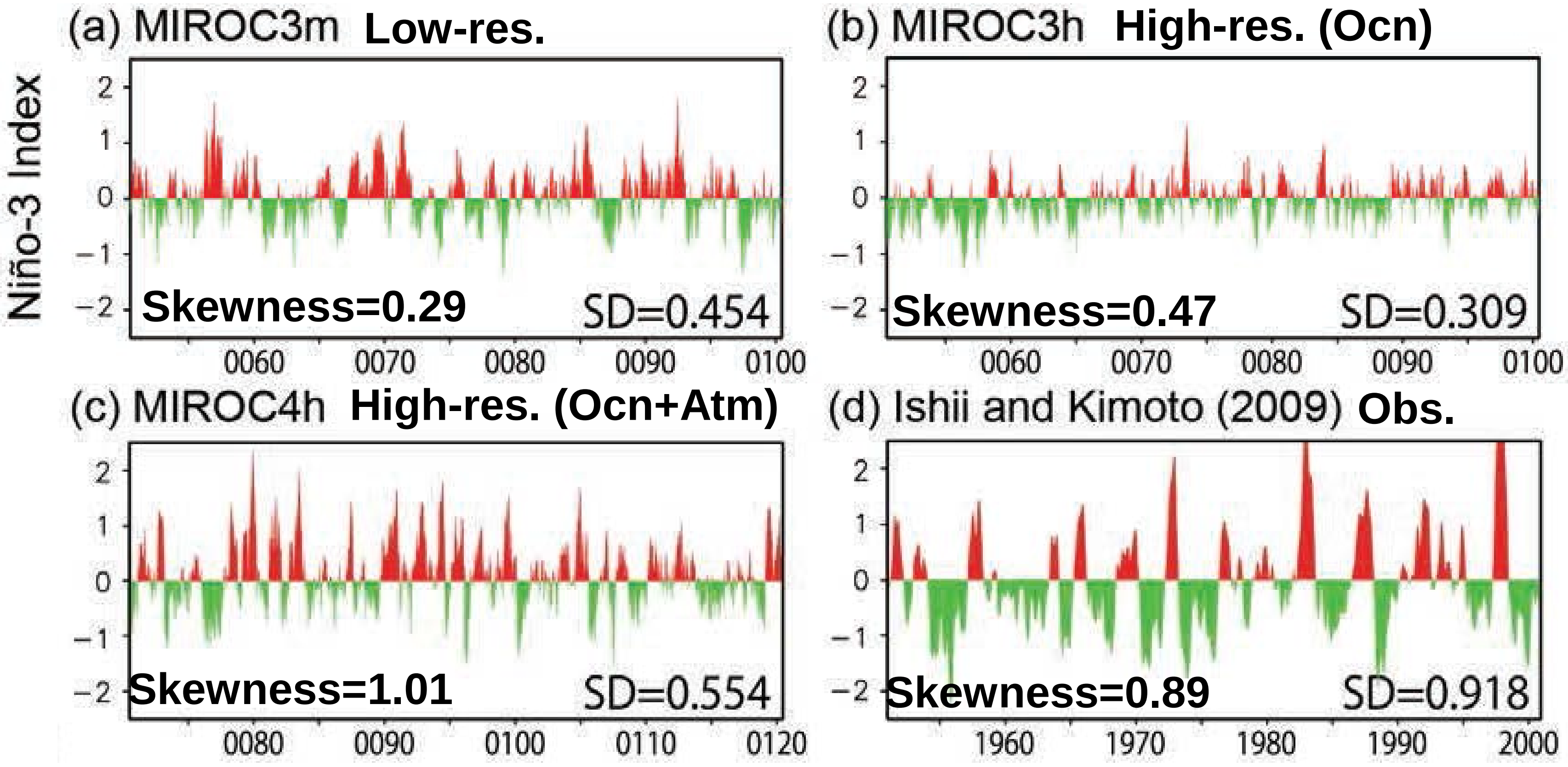
Sakamoto et al. 2012

cf. An (2008) , JC

Jochum and Murtugudde (2006) , JPO

ENSO and TIW

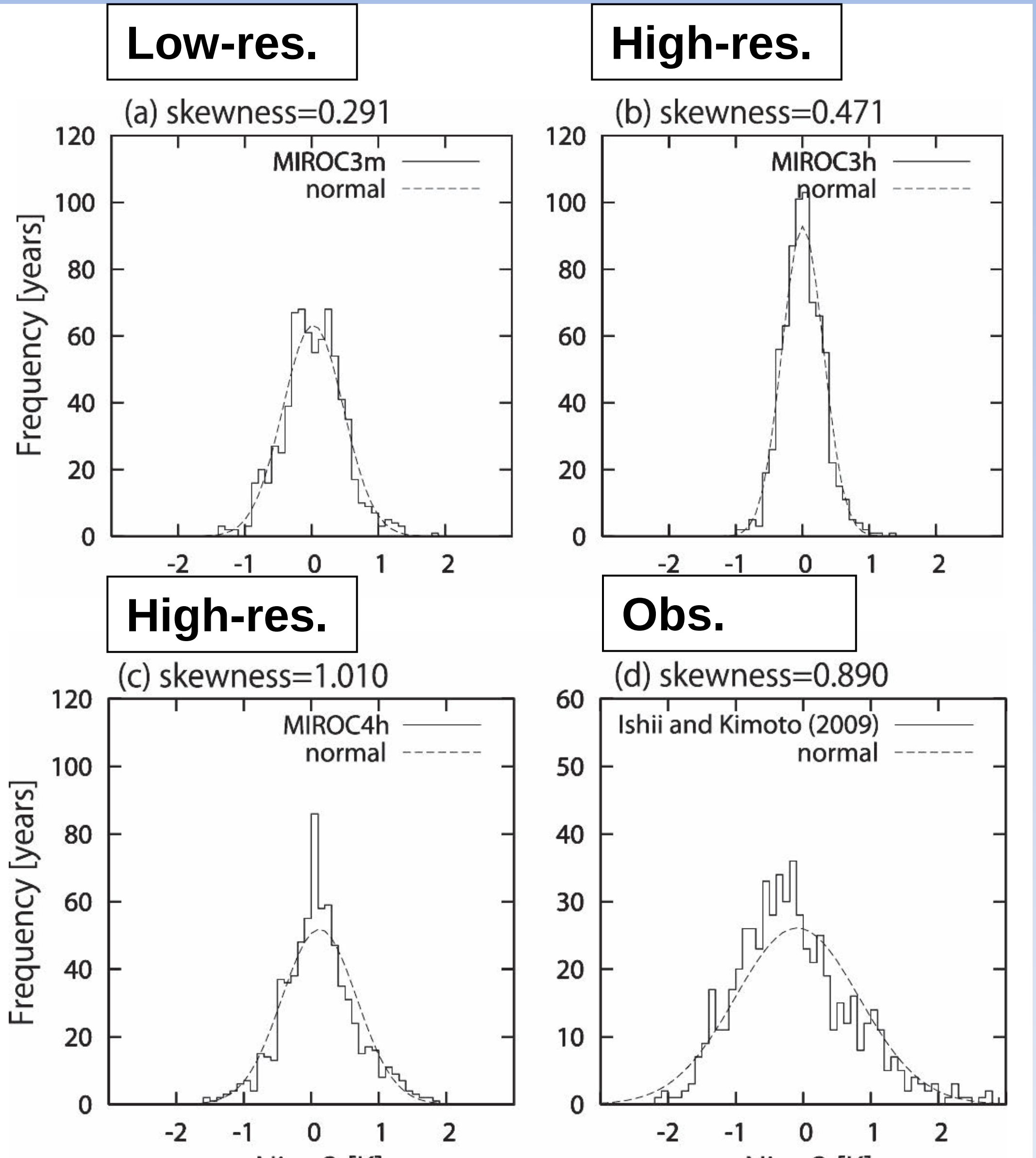
Nino-3 indices from high-res., low-res. models and an observation.



Sakamoto et al. 2012

cf. Imada and Kimoto (2012), An (2008)

ENSO and TIW



Histograms of probability density distributions of Nino-3 indices from (a) MIROC3m, (b) MIROC3h, (c) MIROC4h, and (d) Ishii and Kimoto (2009). Dashed line shows a normal distribution. Skewness for each Nino-3 index is also noted.

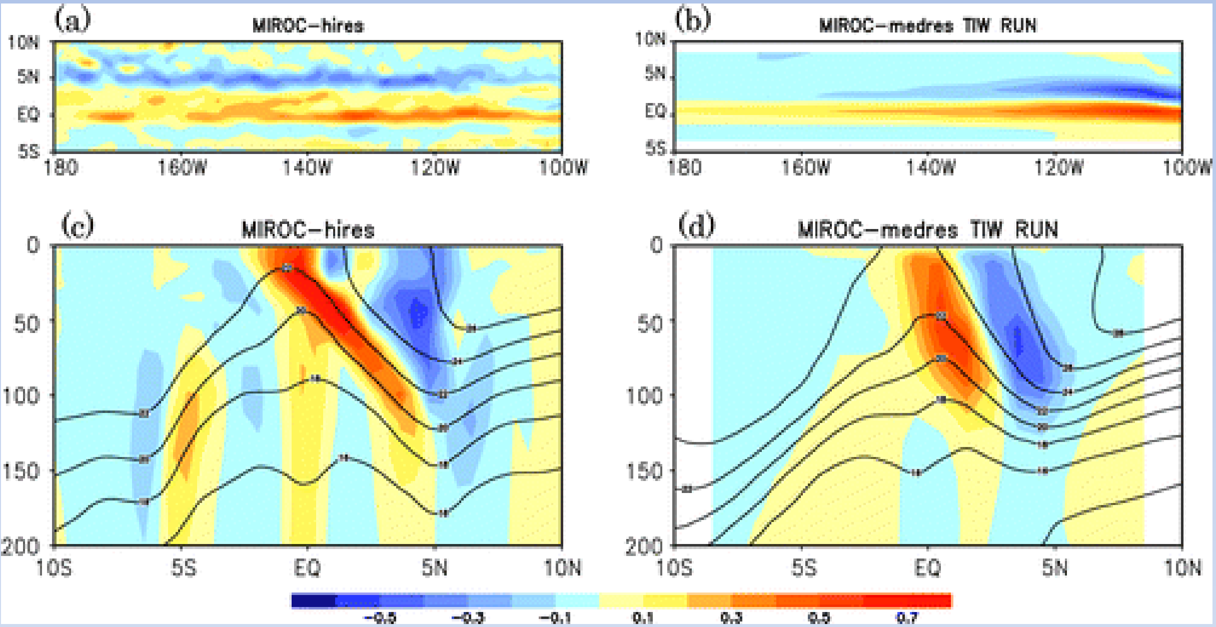
Sakamoto et al. 2012

cf. Imada and Kimoto (2012), An (2008)

ENSO and TIW

High-res. model

Low-res. Model w/ TIW parameterization



Imada and Kimoto (2010) introduced a new TIW parameterization.

(upper)

Horizontal eddy heat flux (averaged from the surface to 100 m depth)

(lower)

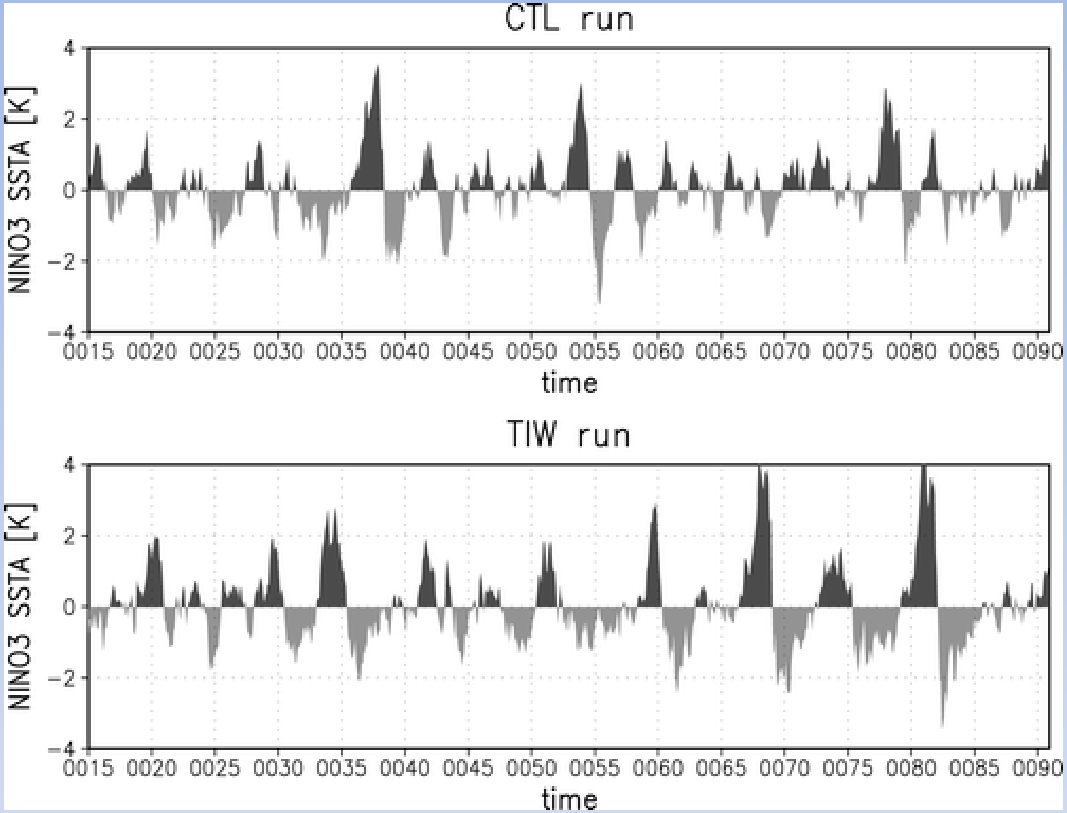
latitude–depth section (at 120° W) of meridional eddy heat flux convergence (1 × 10^{-6} K s^{-1}).

The results imply that nonlinearlity of ENSO would be improved if the TIWs are parameterized or resolved in CGCMs.

Imada and Kimoto 2012 cf. Sakamoto et al. 2012

ENSO and TIW

Time series of SST anomalies averaged over the Niño-3 region calculated from (top) Low-res. Model w/o TIW parameterization (bottom) Low-res. Model w/ TIW parameterization.



The results imply that the El Niño–La Niña asymmetry would be improved if the TIWs are parameterized or resolved in CGCMs.

Imada and Kimoto 2012, cf. Sakamoto et al. 2012

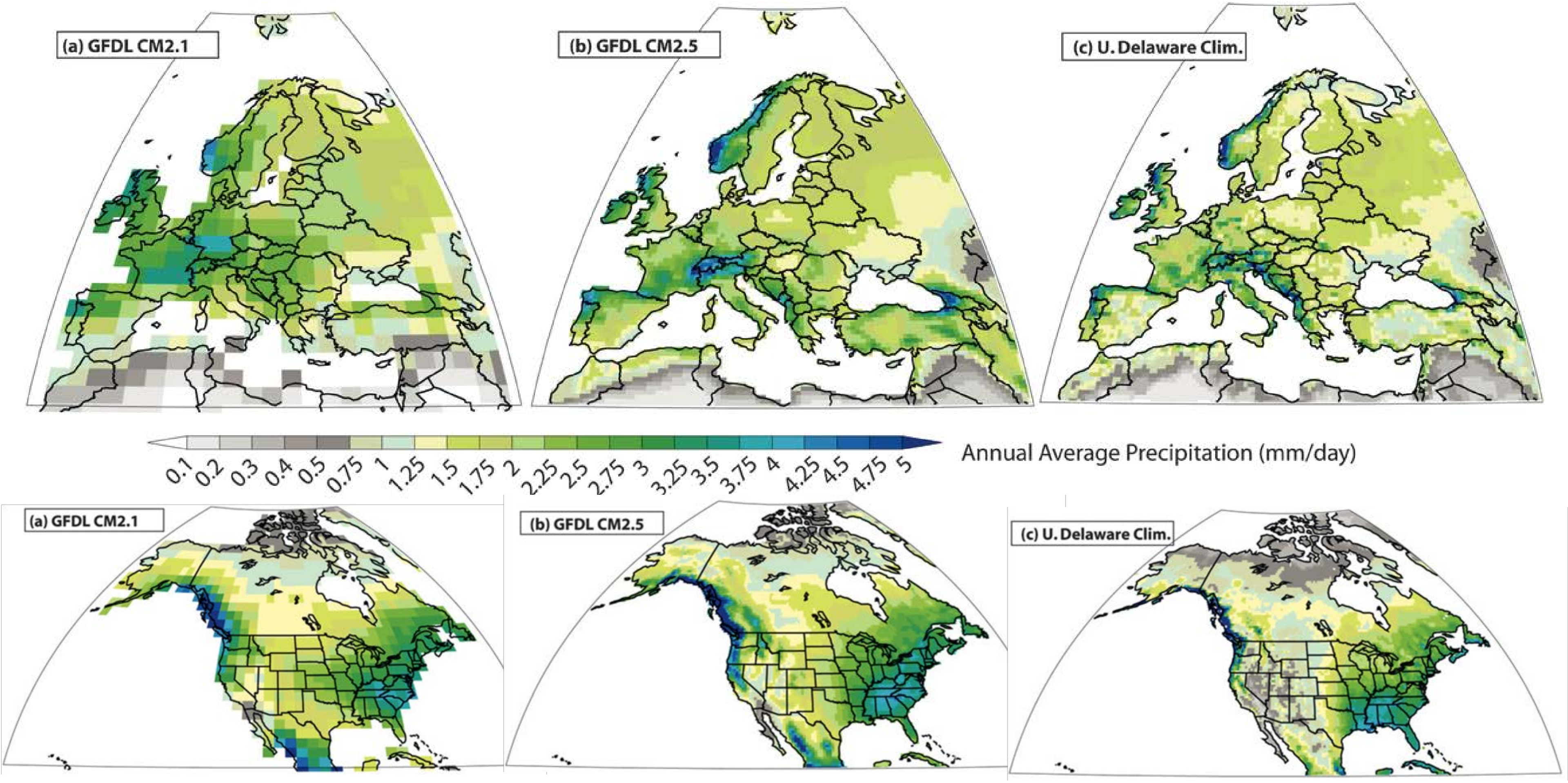
High-resolution atmospheric model for seasonal forecasting

Impacts of the atmospheric model resolution for the seasonal forecast has been of interest for long time.

Tibaldi et al. (1990) QJRMS
Boyle (1993) MWR
Brankovic and Gregory (2001) Clim. Dym.
…

Recent studies including very high resolution of state-of-the-art models had also discussed this topic.

Annual Mean Precipitation

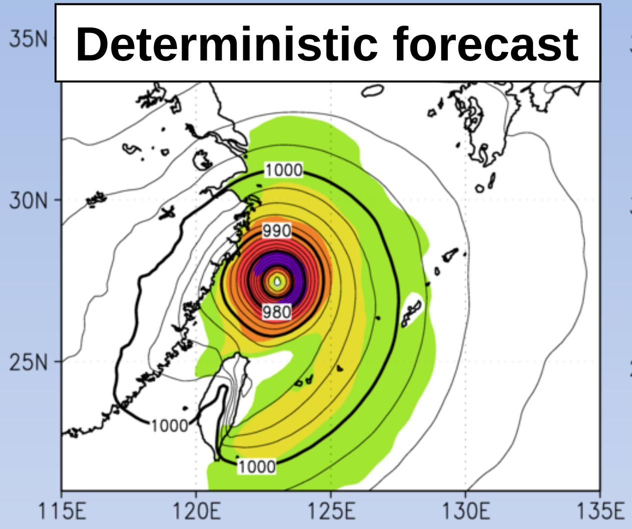


CM2.1 atm: 200 km, ocn: 100km
CM2.5 atm: 50 km, ocn: 28km

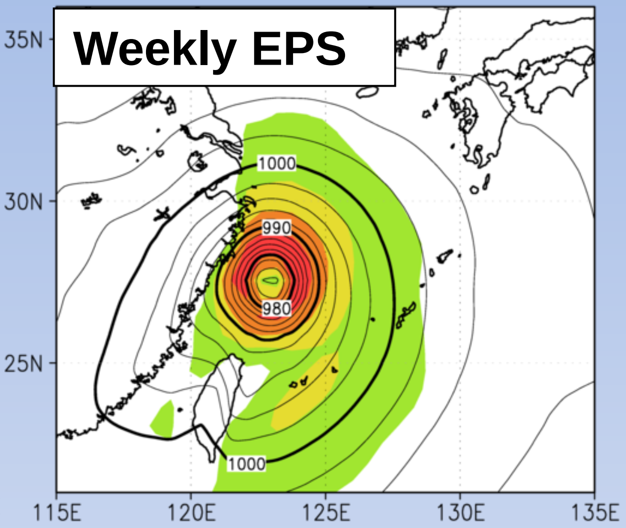
Delworth et al. 2012

Tropical Cyclone

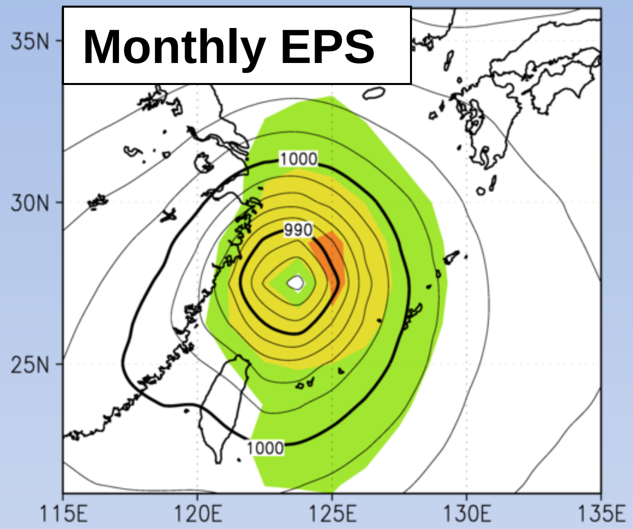
Resolution of 20km



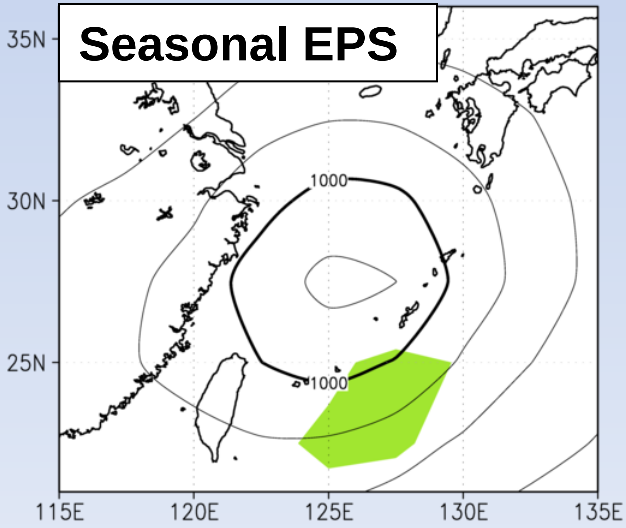
Resolution of 55km



Resolution of 110km



Resolution of 180km

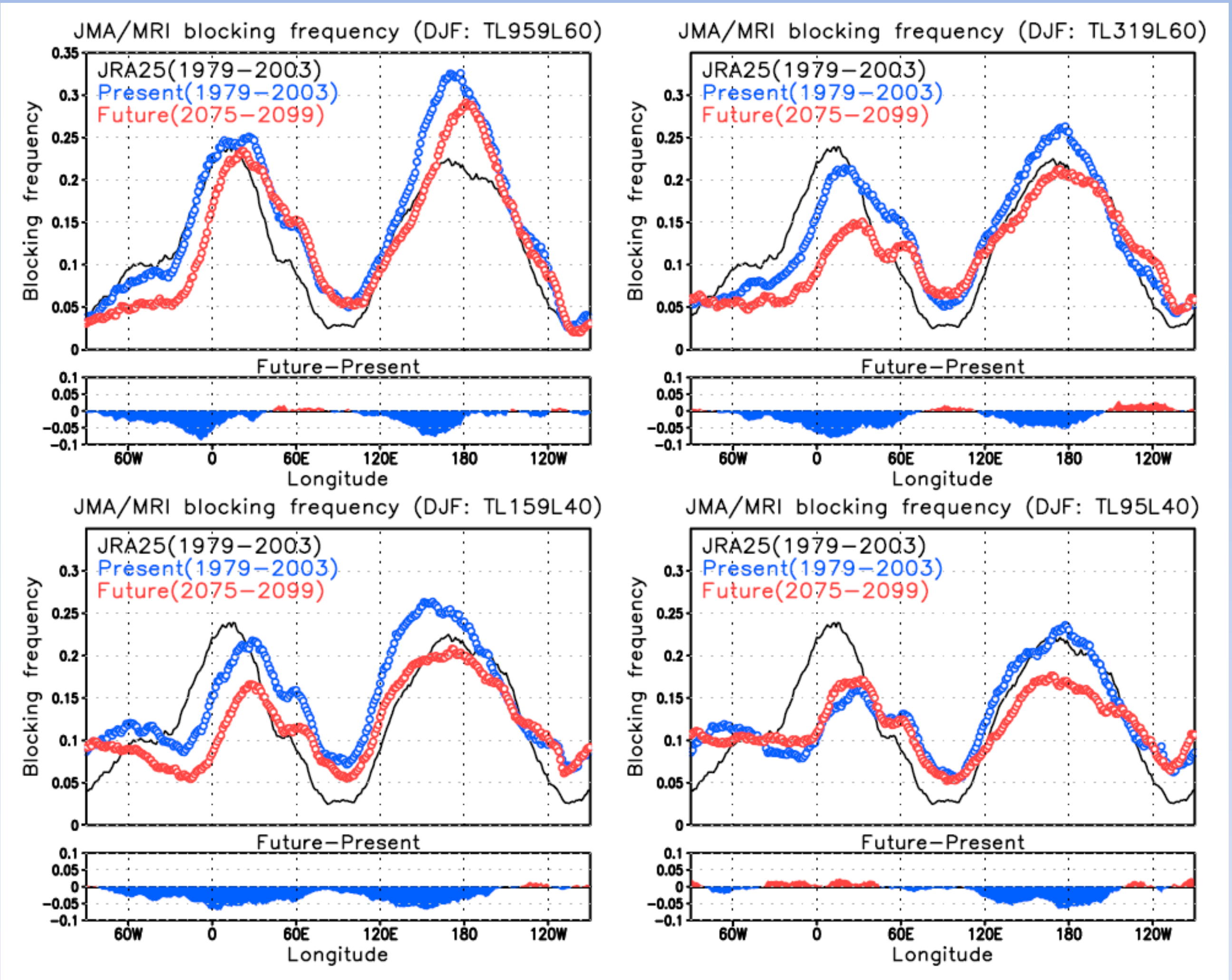


Surface wind speed around TY1211 (HAIKUI) at 00 UTC 7 Aug 2012 (Initial time: 12UTC 5 Aug 2012)

* The I.C. of seasonal EPS is one day older than the others, and interpolated to 2.5 deg. grid.

cf. Manganello et al. 2012, Walsh et al. 2012

Blocking



Frequency of Northern Hemisphere wintertime blocking as a function of longitude for JMA/MRI AGCMs with four different resolutions: **(top left) TL959L60 (20 km), (top right) TL319L60 (60 km), (bottom left) TL159L40 (120 km), and (bottom right) TL95L40 (180 km).** The black, blue, and red lines represent JRA25 (1979–2003), present-day (1979–2003), and future (2075–2099) climate runs, respectively.

Improvements of parameterizations also contribute to better representation.

cf. Berner et al. 2012 J. Clim.

Matsueda et al. 2009

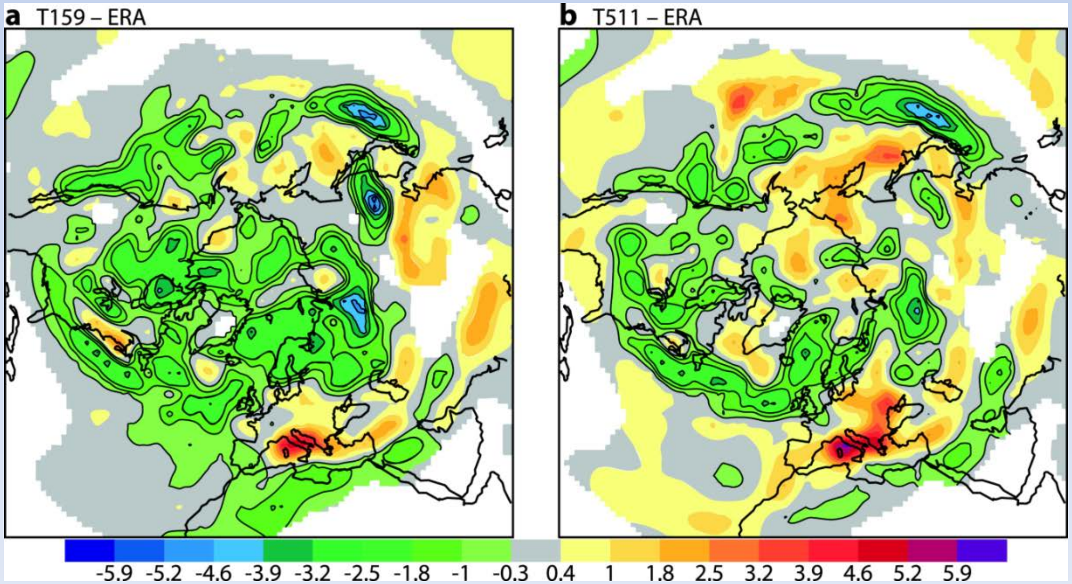
cf.) Jung et al. 2012 JC

Project Athena (1)

T159(126km), T511 (39km), T1279(16km), T2047(10km) simulations with ECMWF model.

Increasing horizontal resolution improves:

- tropical precipitation, tropical atmospheric circulation (related to time-step?),
- frequency of occurrence of Euro-Atlantic blocking (related to orography?),
- extratropical cyclones in large parts of the NH extratropics.
- Skill of seasonal prediction might be slightly increased in in the tropics and NH in boreal winter with T1279. No dicernible effect for summer.
- Problems in simulating MJO remain unchanged.

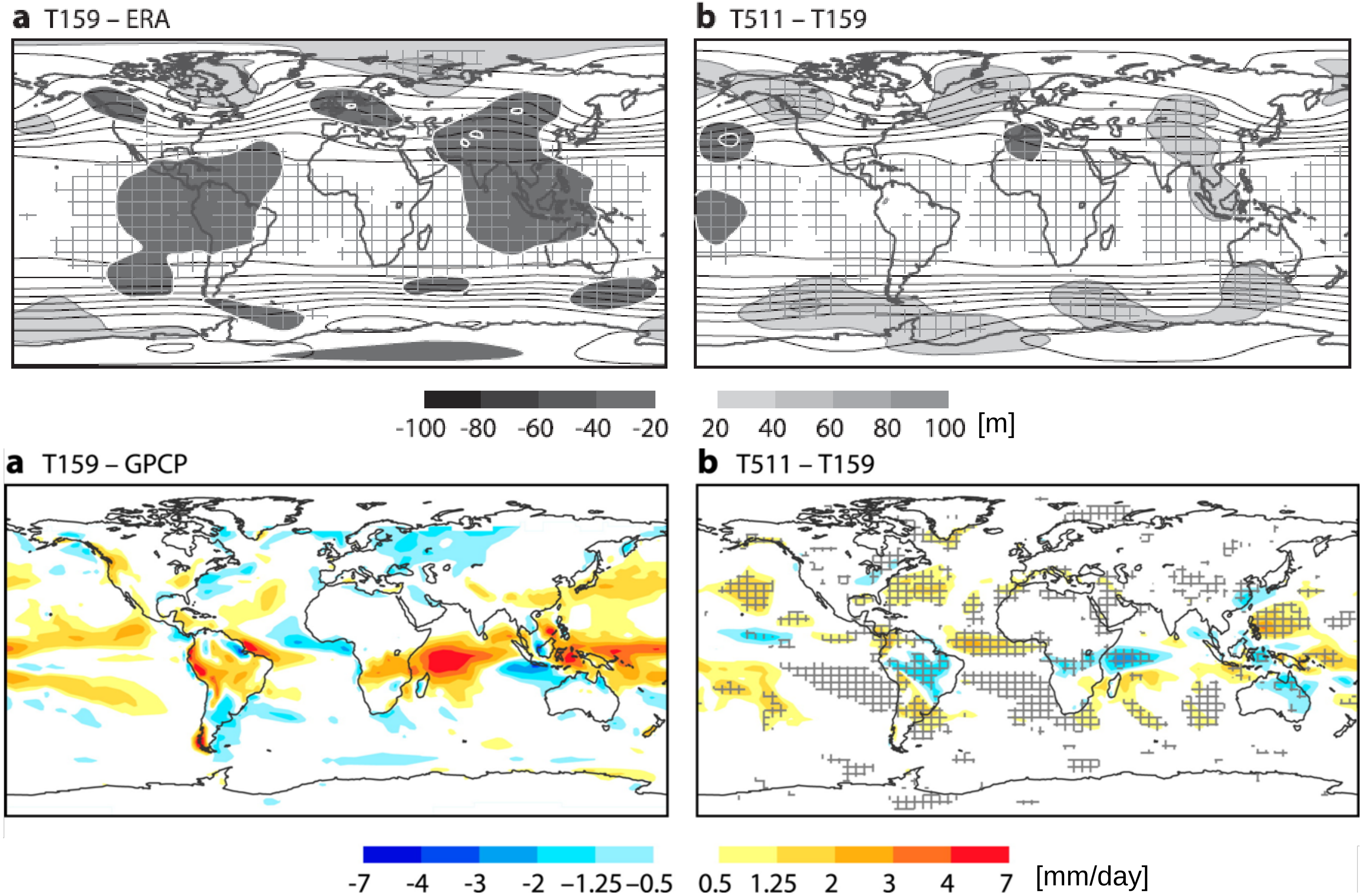


Differences in **track density** of vorticity maxima at 850 hPa from 13-month integrations for winters (DJF) during the period 1989/90–2007/08: (a) T159–ERA-Interim, (b) T511–ERA-Interim,

Jung et al. 2012

See also, Jung et al. 2006

Project Athena (2)



Differences in average (upper) **500-hPa geopotential height** and (lower) **precipitation** fields from 13-month integrations for winters (DJF) during 1989/90–2007/08: (a) T159–Reanalysis, (b) T511–T159

Implication from High-resolution modellding

- High-resolution models would improve:
  - Meso-scale eddy activity, small-scale features in the wind stress curl around islands and oceanic SST fronts,
  - Cold tongue SST bias (ENSO mean states and variability),
  - Cold SST drift in the North Atlantic,
  - ….
- Increase both of atmosphere and ocean resolutions may be important. (cf. Roberts et al. 2004). Atmospheric model resolution about at least 100 km would be necessary so as to be able to respond to the fine-scale details in the ocean-surface properties.

  (Shaffrey et al. 2009, Sakamoto et al. 2012)
- Eddy-resolving ocean models change coupled models' performance drastically. (Delworth et al. 2012, Kirtman et al. 2012)

Some efforts and approaches

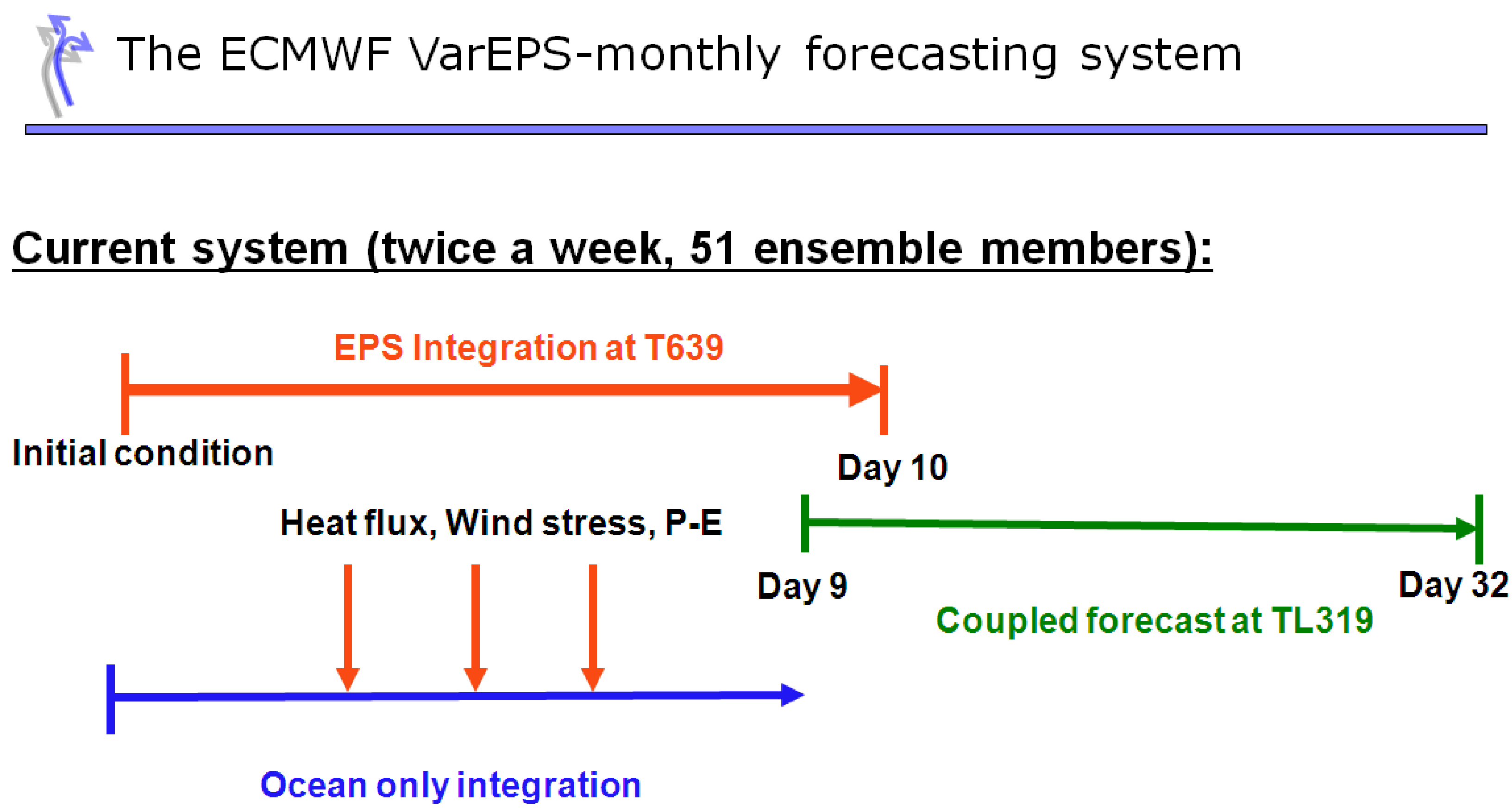
Some efforts and approaches

- High-res. coupled model (straight way)

- Two tier system -> one tier system
- Variable-resolution prediction system
- Increasing resolution in atmospheric models
  - Horizontal resolution
  - Vertical resolution/ high-top model
- Ocean nesting in coupled model
- High resolution ocean data assimilation
- Alternative model for future HPCs

Variable-resolution prediction system (1) - ECMWF example -

Buizza et al. (2007, QJRMS), Vitart et al. (2008, QJRMS)



The ECMWF VarEPS-monthly forecasting system

Current system (twice a week, 51 ensemble members):

EPS Integration at T639

Initial condition

Day 10

Heat flux, Wind stress, P-E

Day 9

Day 32

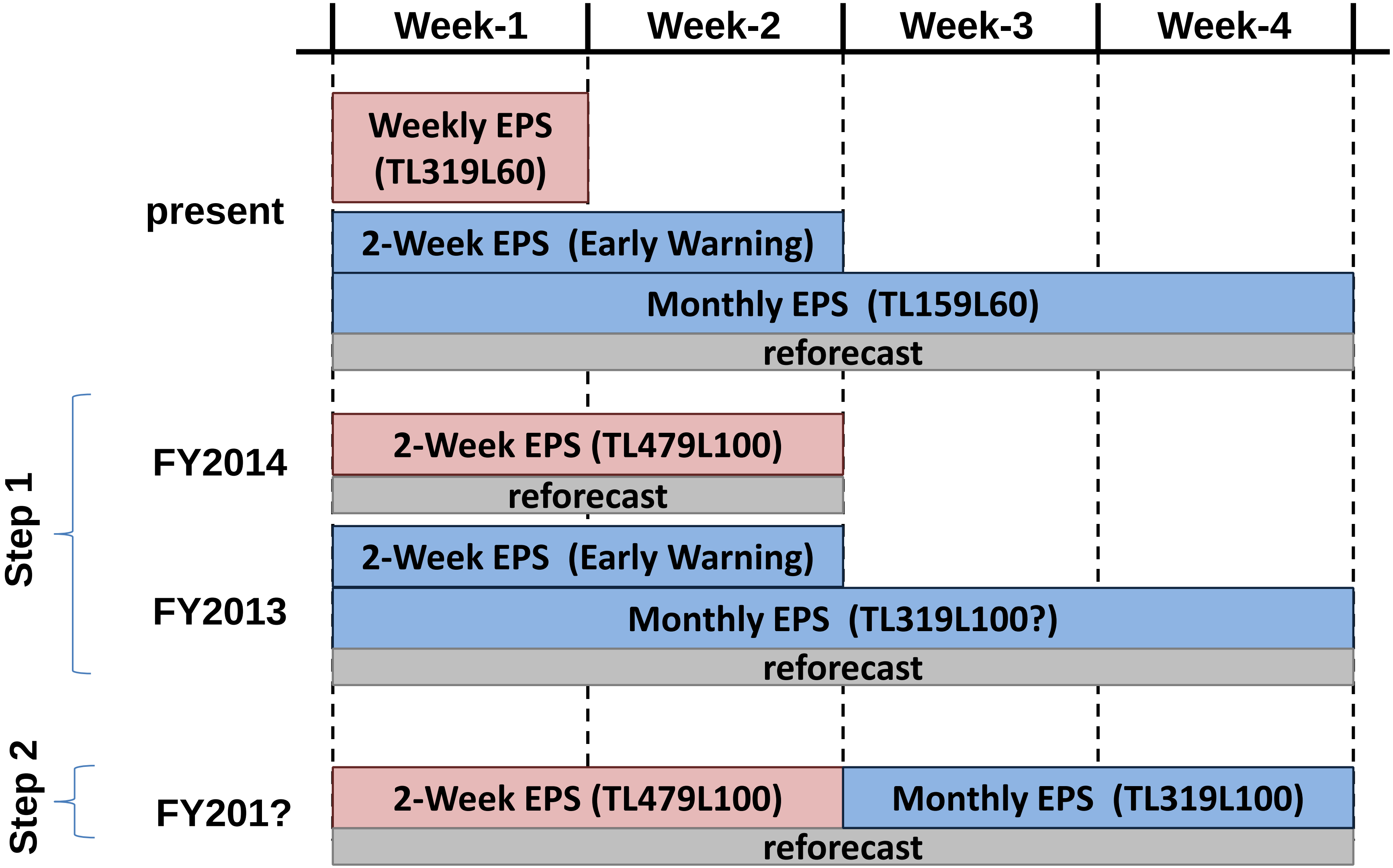
Coupled forecast at TL319

Ocean only integration

From a presentation of Frederic Vitart at WWRP/THORPEX, WCRP Kick off meeting of Sub-seasonal to Seasonal Prediction (Geneva, 2011)

*** The current ECMWF Monthly EPS is fully coupled.**

Variable-resolution prediction system (3) - JMA plan -



Week-1 Week-2 Week-3 Week-4

present

Weekly EPS (TL319L60)

2-Week EPS (Early Warning)

Monthly EPS (TL159L60)

reforecast

Step 1

FY2014

2-Week EPS (TL479L100)

reforecast

FY2013

2-Week EPS (Early Warning)

Monthly EPS (TL319L100?)

reforecast

Step 2

FY201?

2-Week EPS (TL479L100)

Monthly EPS (TL319L100)

reforecast

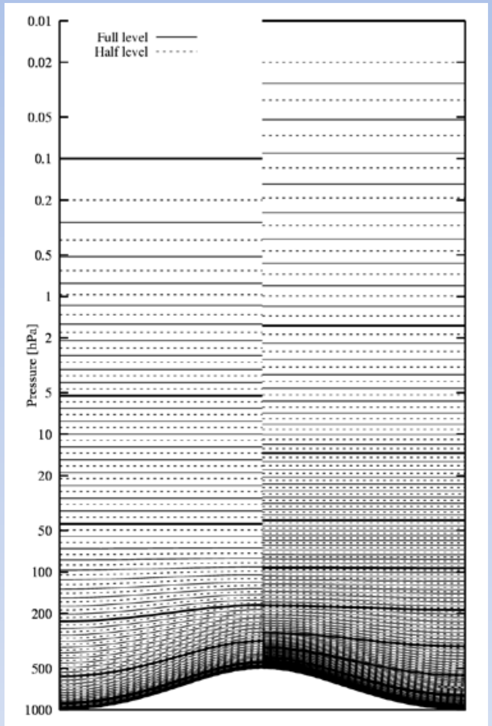
* All systems are currently planned to be uncoupled systems.

Vertical resolution of AGCM

High-top is better!

Burj Khalifa Dubai
829.84 m, 160 levels
Opened January 2010

But… it costs a lot!



Next JMA Model
high-top & high-resolution
~80 km, 100 levels
(under development)

Stratospheric influence on the troposphere

Downward propagation of annular mode

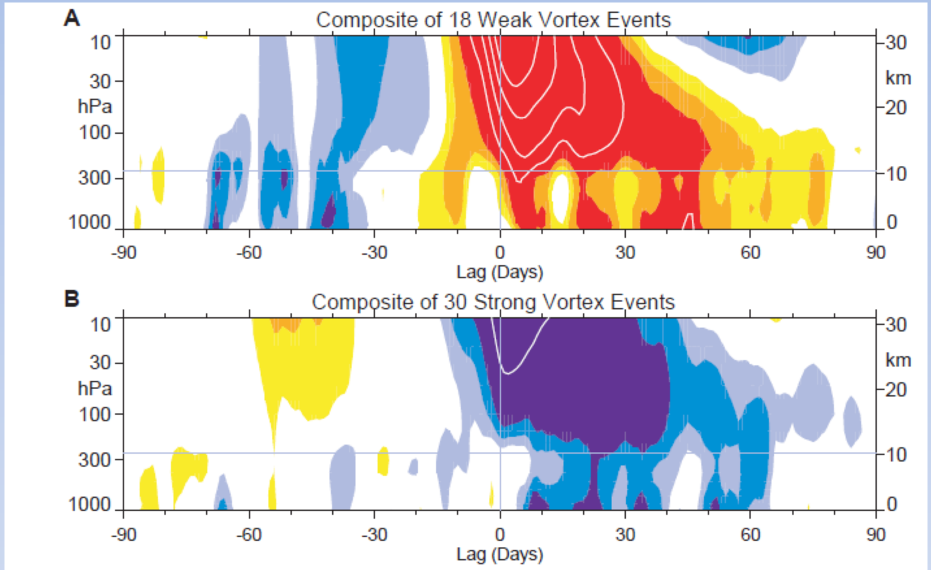
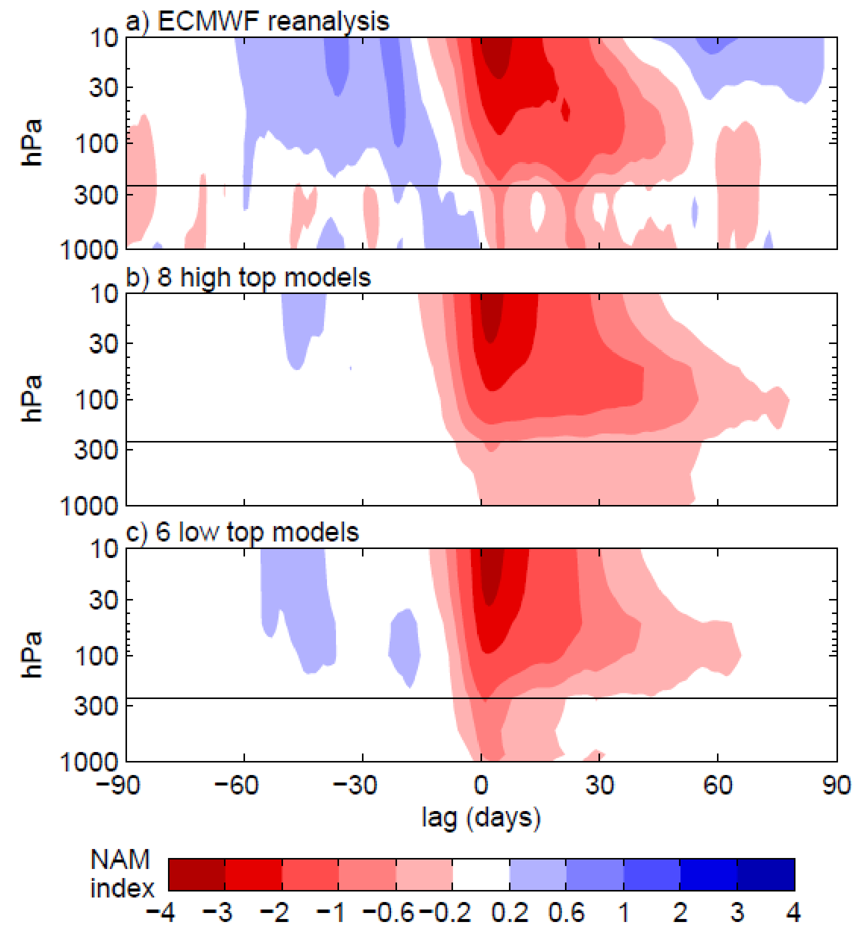


Fig. 2. Composites of time-height development of the northern annular mode for (**A**) 18 weak vortex events and (**B**) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular mode values cross –3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between −0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and the stratosphere.

Baldwin and Dunkerton 2001 Science

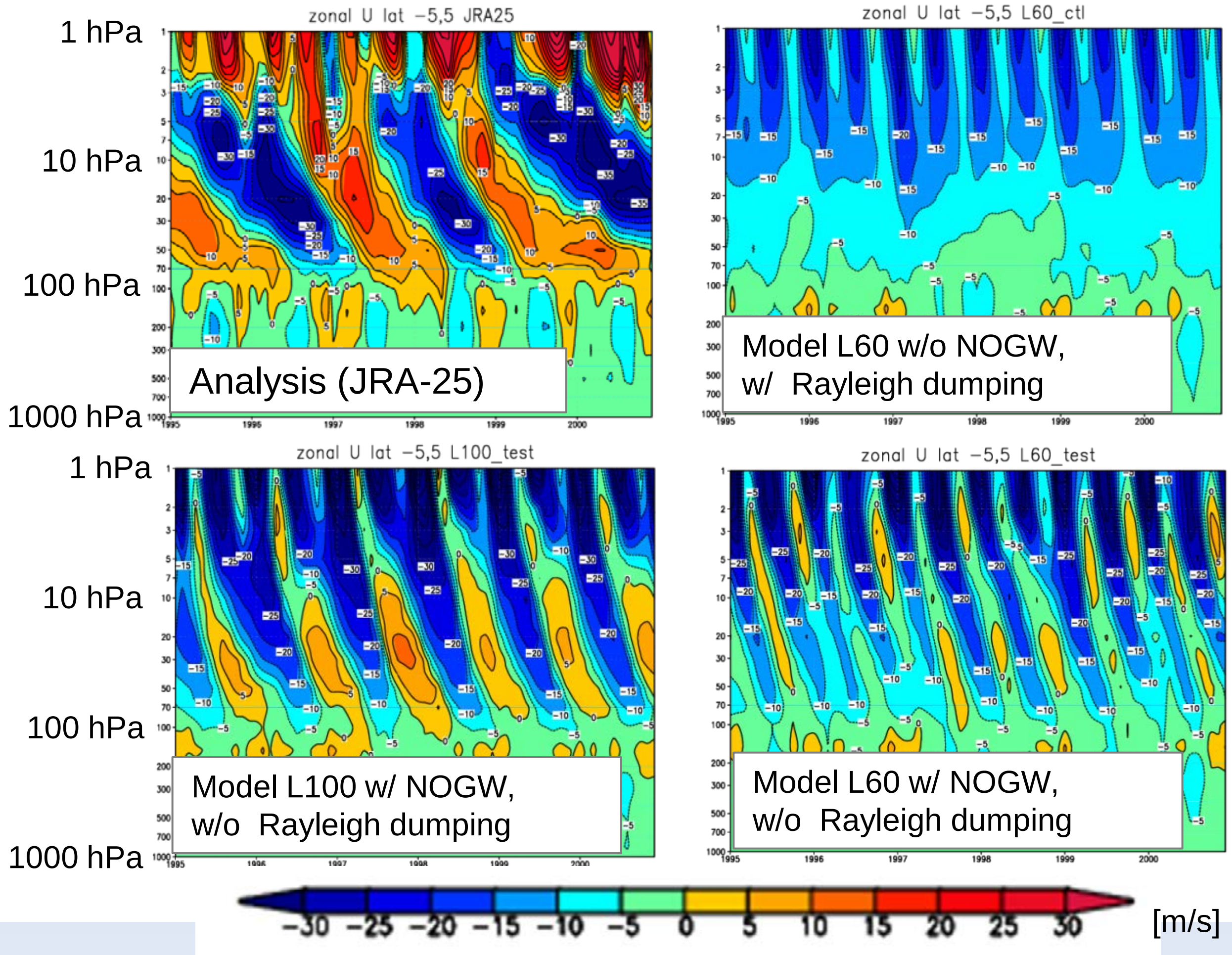
CMIP5 simulations



Charlton-Perez et al. submitted to JGR

Development of high-top & high vertical resolution model

Only increasing vertical levels doesn't give satisfactory results, appropriate treatments in model physics, analysis would be needed.



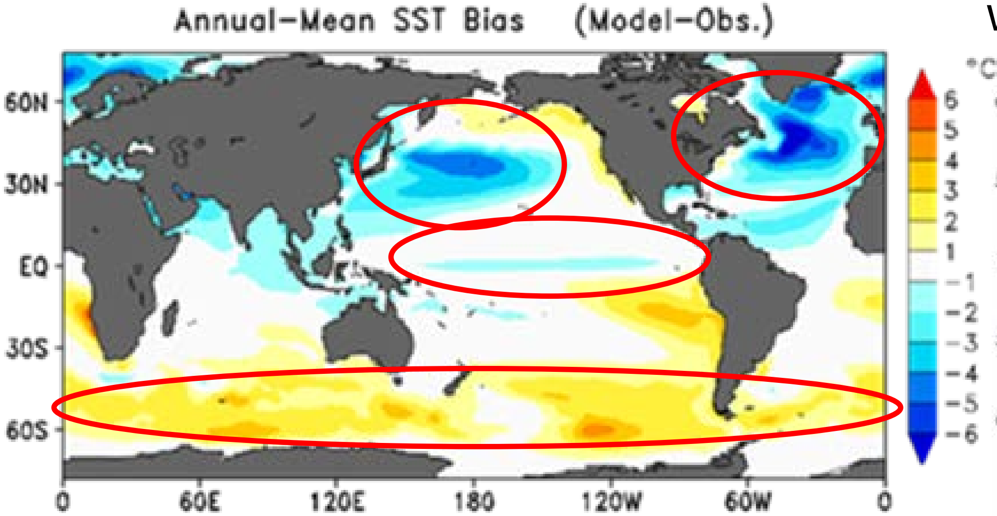
Time-vertical cross section of zonal wind averaged over 5N-5S from 6-year simulations.

Comparison with a newly developed non-orographic gravity wave parameterization (Scinocca 2003).

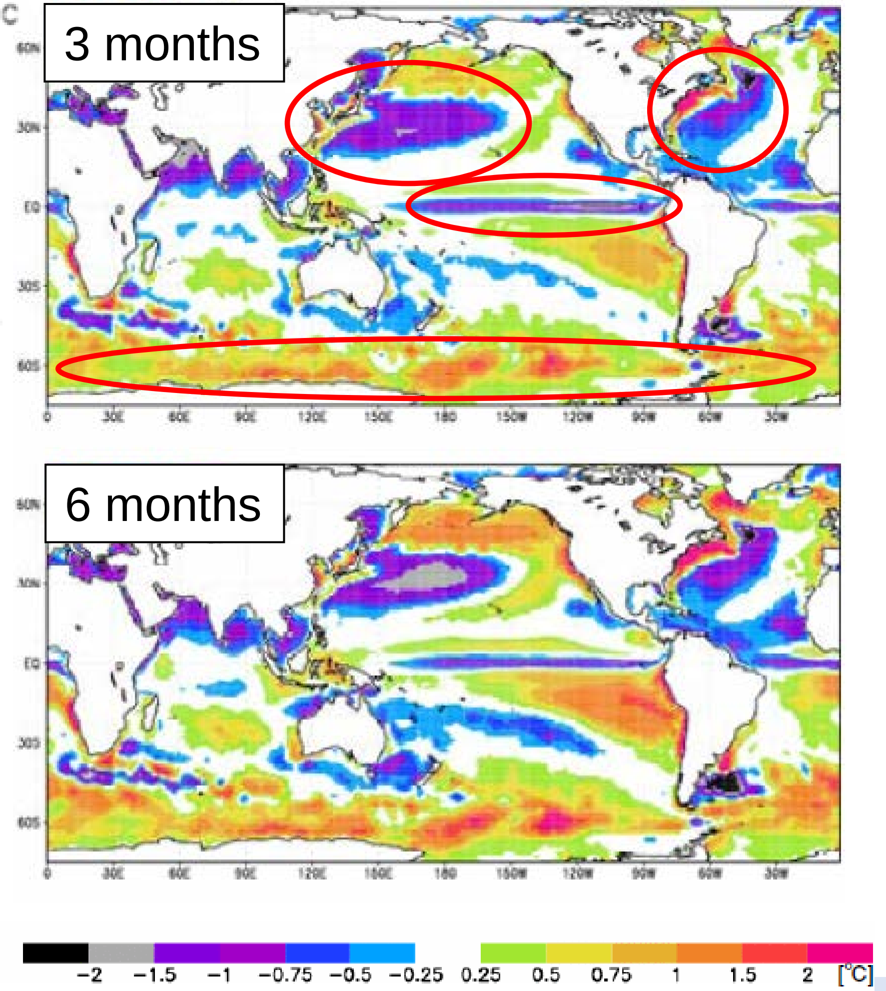
Takafumi Kanehama (NPD/JMA)

Ocean nesting in coupled model

SST mean biases in JMA CMIP5 model



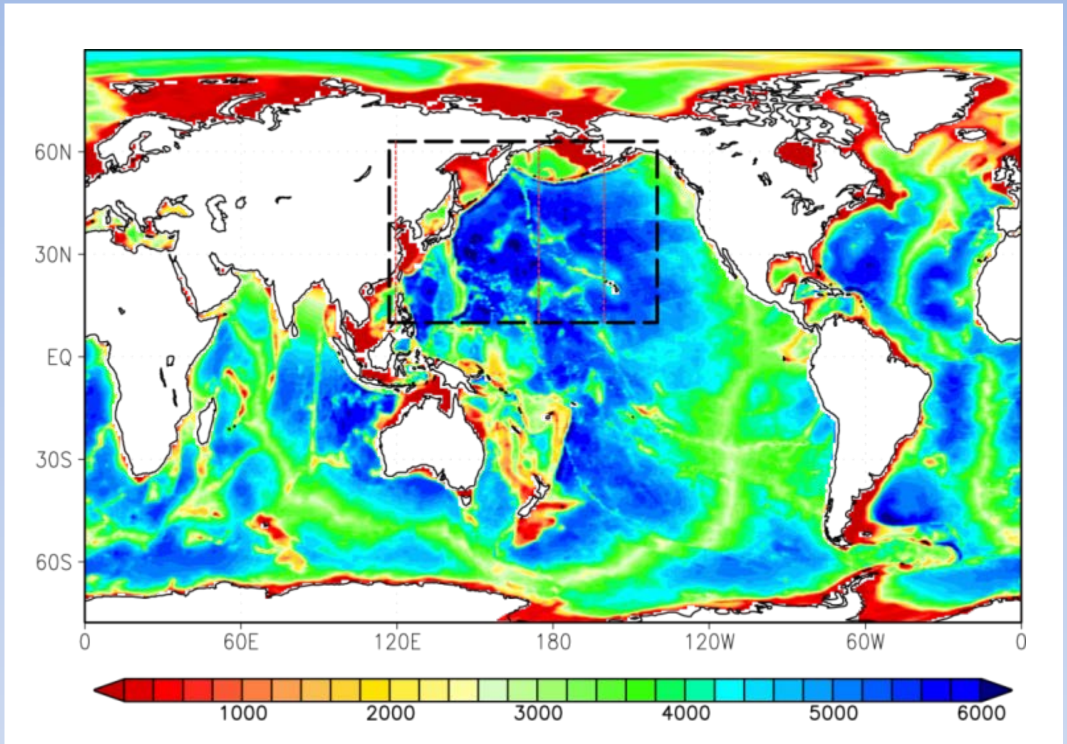
SST biases (JMA/MRI-CGCM reforecasts without flux adjustments: 1979-2007)

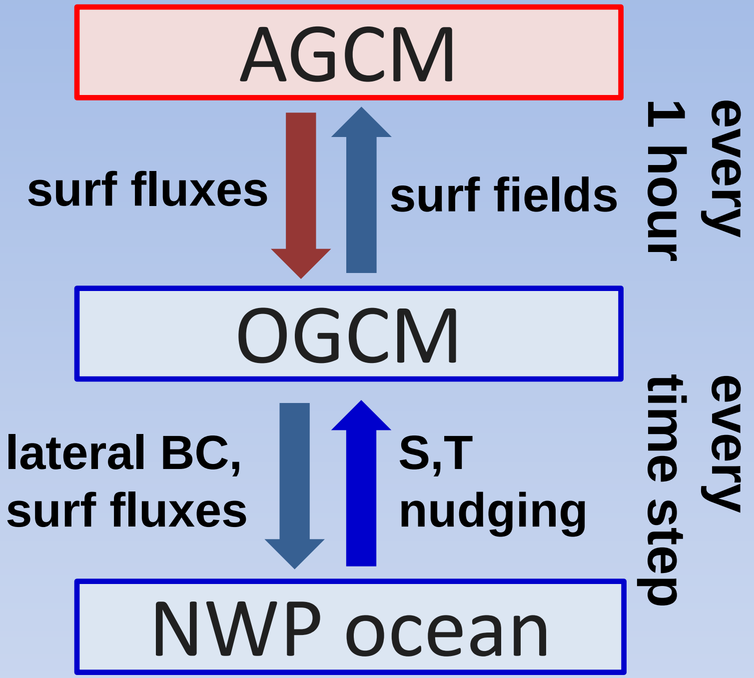


JMA coupled models share common biases in a SST field, which may be at least partly attributed to lack of ocean-model resolution.

Hiroyuki Tsujino (MRI/JMA)

North Western Pacific nested model





AGCM

surf fluxes

surf fields

every 1 hour

OGCM

lateral BC, surf fluxes

S,T nudging

every time step

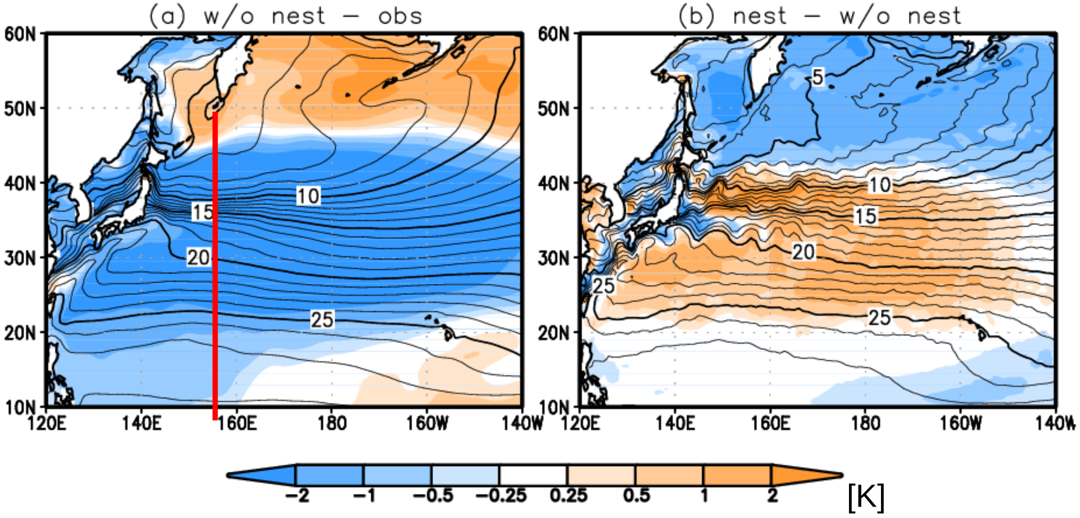
NWP ocean

- Global model (tri-polar grid, lon: 1 deg., lat: 0.5 deg., 50 layers) Number of grids: 364 x 368 x 51
- North Western Pacific model (117E-140W (1/7-1/11),10-63N(1/10)) Number of grids: 995 x 534 x 51 (4 times as much as the global model)
- Coupled at every time step with an efficient coupler (SCUP)
- dt = 6 [min]

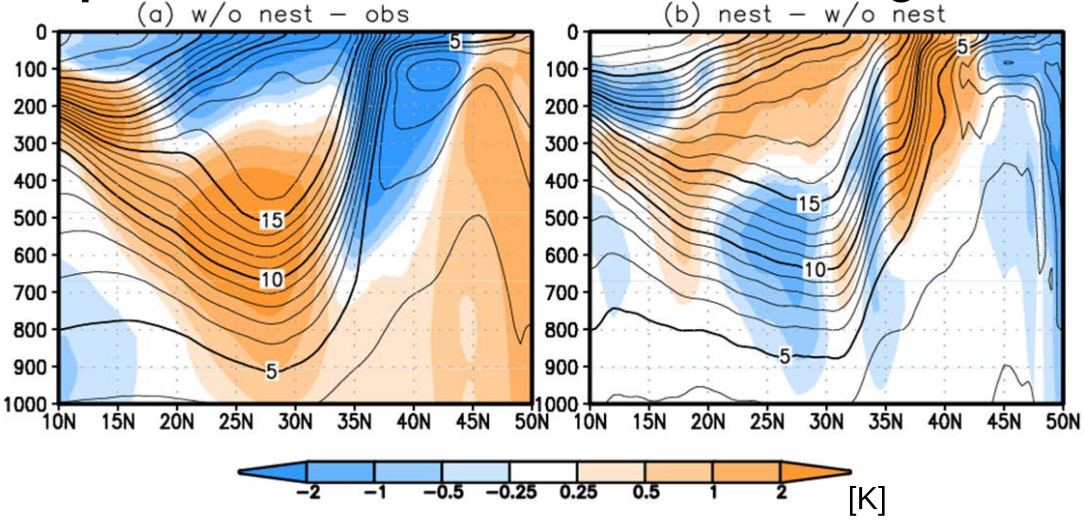
Hiroyuki Tsujino (MRI/JMA)

Impacts of the nested ocean model

SST climatology (1989-1993)



Temperature vertical cross section along 155E



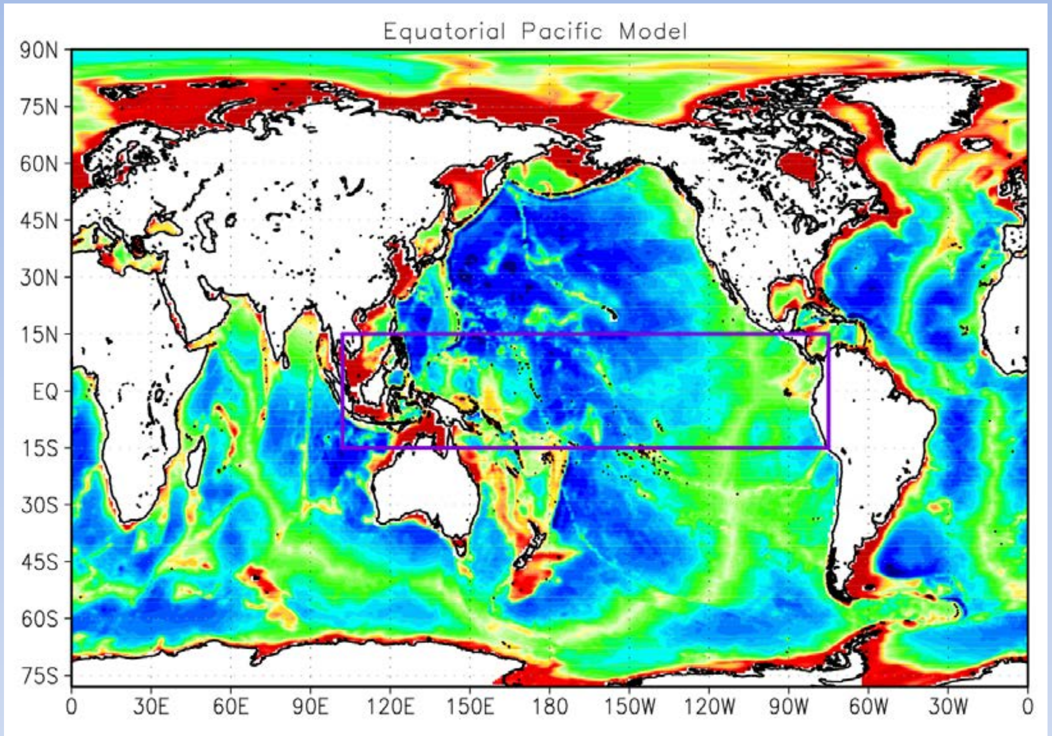
Left:
Simulation w/o nesting minus observation (WOA98)

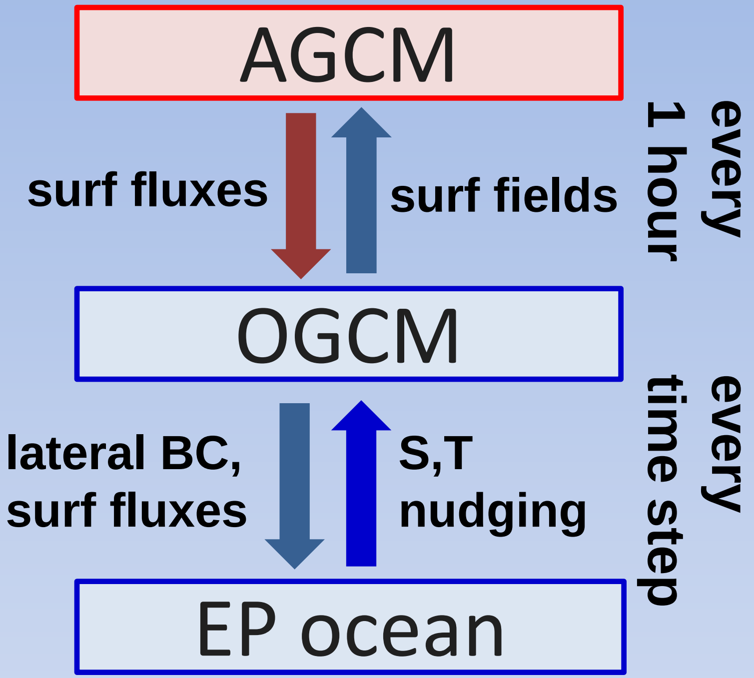
Right:
Simulation w/ nesting minus w/o nesting

The Gent-McWilliams isopycnal mixing is applied only to global (host) model.

Hiroyuki Tsujino (MRI/JMA)

Equatorial Pacific nested model





AGCM

surf fluxes

surf fields

every 1 hour

OGCM

lateral BC, surf fluxes

S,T nudging

every time step

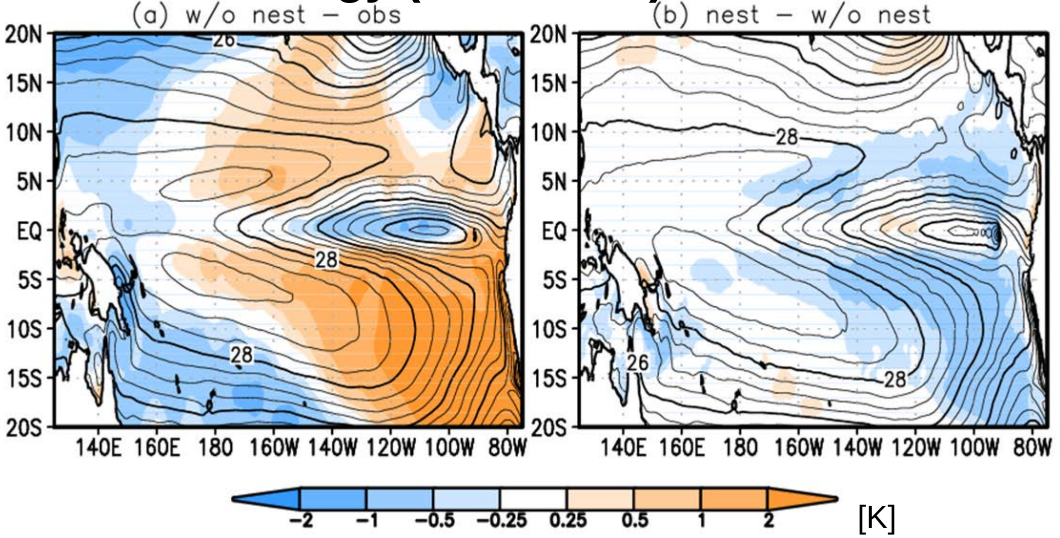
EP ocean

- Lon: 1/5, lat: 1/6
- Number of grids 1.25 times as much as the global model
- dt = 20 [min] (similar to OGCM)

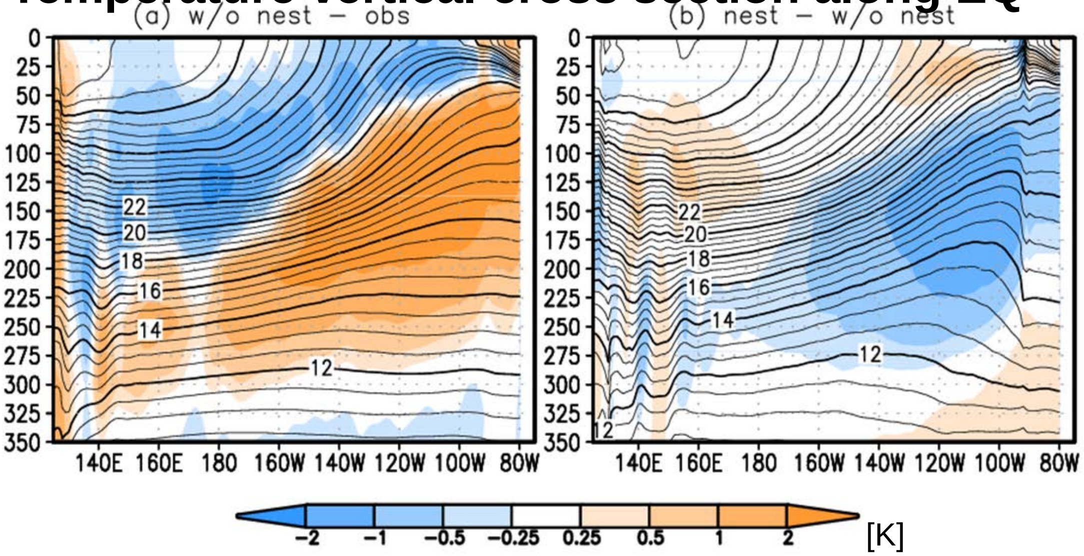
Hiroyuki Tsujino (MRI/JMA)

Impacts of the nested ocean model

SST climatology (1989-1993)



Temperature vertical cross section along EQ



Left:
Simulation w/o nesting minus observation (WOA98)

Right:
Simulation w/ nesting minus w/o nesting

Hiroyuki Tsujino (MRI/JMA)

Globally intermediate resolution or nested ?

-Upgrade from **1 x 0.5** to **0.5x0.5** would have marginal impacts.

- **Eddy permitting 0.25 x 0.25**

  Poor representation of Kuroshio meander, and separation of boundary current.

  CPU cost is 16 times (4(lon)x2(lat)x2(time)).

- **Eddy resolving 0.1x0.1**

  CPU cost is 200 times (10(lon)x5(lat)x4(time).

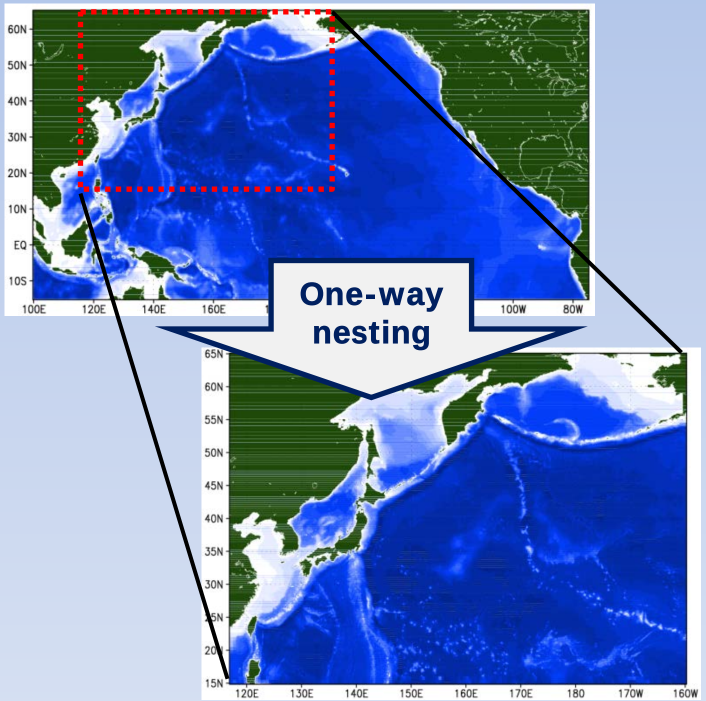
- **Nested model**

# of Grid	Tropics:	2.33 times
	North Western Pacific:	1.50
	North Atlantic:	1.85
	Global:	1

If the time step of the high-res.
dt = 10min→ 20min, then
CPU time would be 13 times.

High-res. ocean data assimilation (1)

MOVE/MRI.COM-WNP


One-way nesting

MOVE/MRI.COM-WNP:

- 117^{o}E-160^{o}W, 15^{o}N-65^{o}N
- 0.1^{o}x0.1^{o}, L54
- 3DVAR with T-S EOF (Fujii and Kamachi 2003)
- Incremental Analysis Updates (Bloom et al. 1996)
- Nested into a North Pacific model (0.5^{o}x0.5^{o})

Courtesy Norihisa Usui, Yosuke Fujii (MRI/JMA)

High-res. ocean data assimilation (2)

Warm water intrusion from the Kuroshio into a coastal area

10-Jan-2000 **29-Jan-2000** **5-Feb-2000**

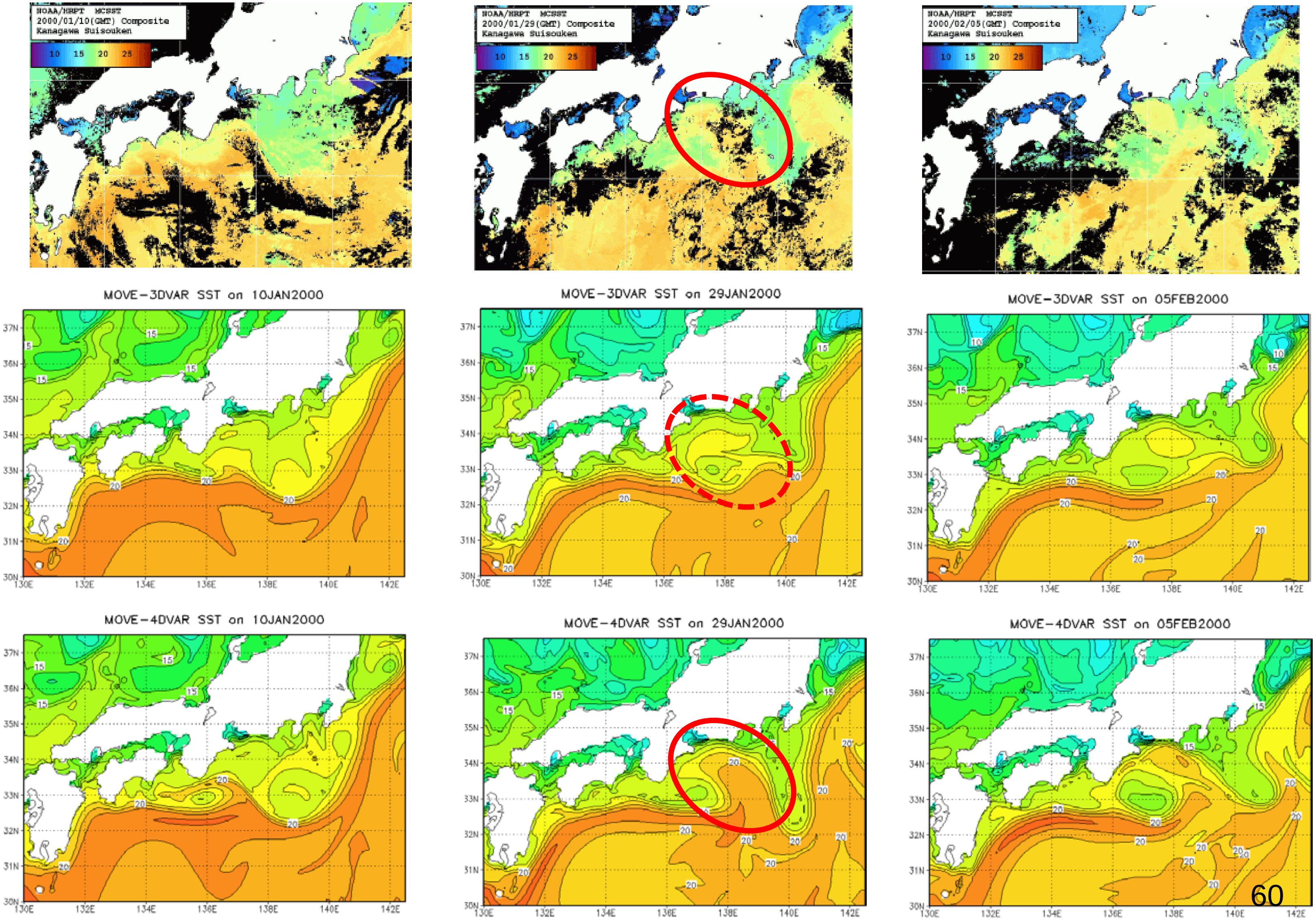
Obs (SST)

3DVAR

(5-day window)

4DVAR

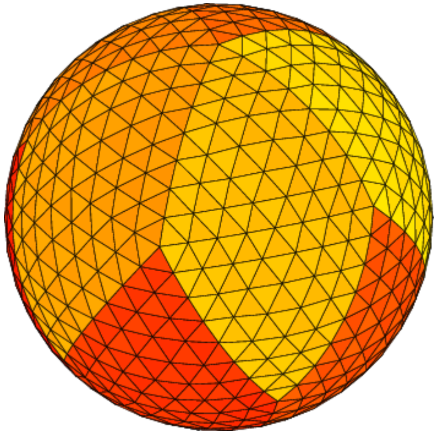
(10-day window)



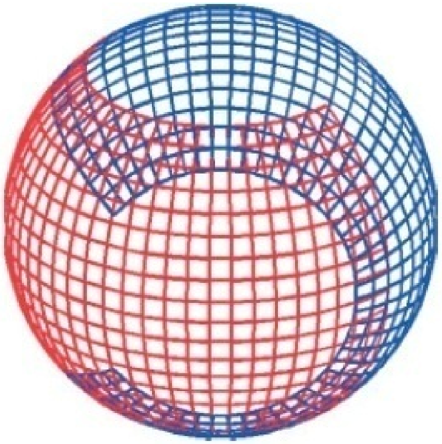
Next generation dynamical cores for climate projection / seasonal prediction (1)

- **AGCMs**
  Substantial efforts have been made to develop new dynamical cores of AGCMs.

Staniforth and Thuburn (2012) QJRMS



Icosahedral grid
NICAM
Satoh et al. 2008



Yin-Yang Grid
Kageyama and Sato 2004
Figure from Staniforth and Thuburn (2012)

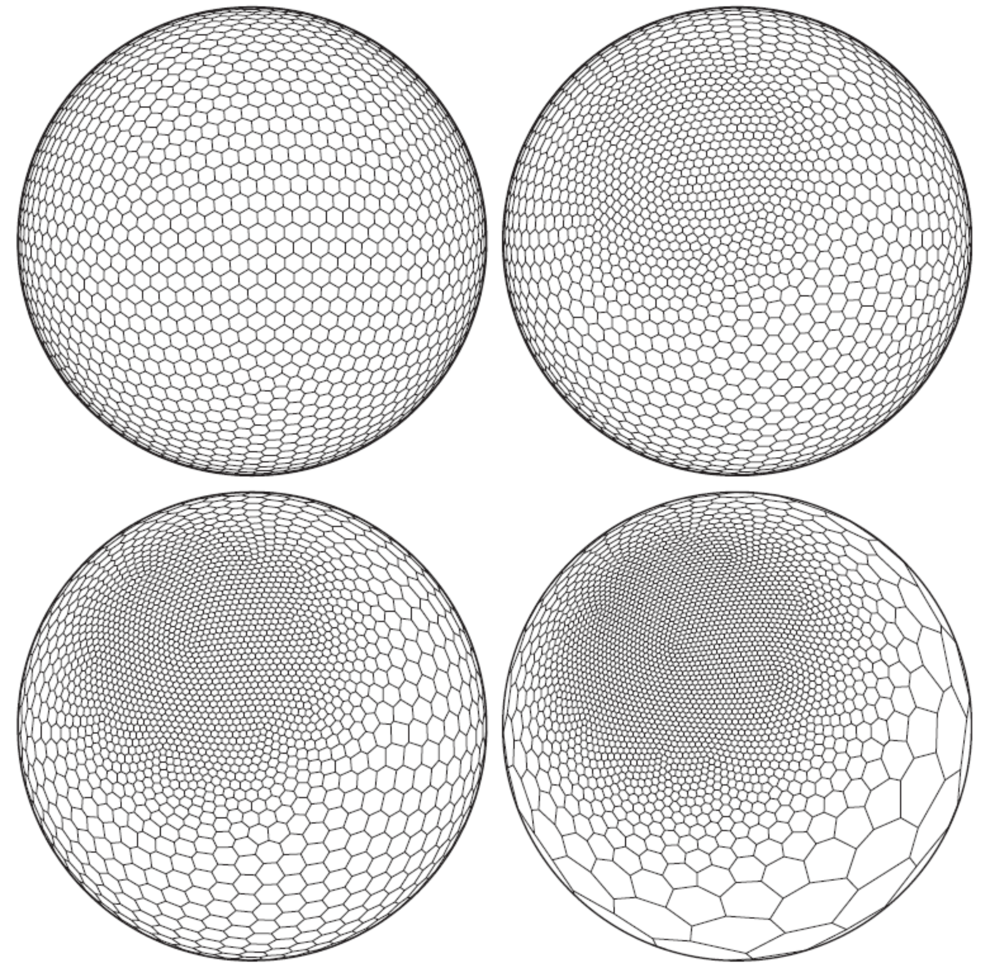
?

Adaptive Mesh Refinement?
cf. Slingo et al. 2009

Next generation dynamical cores for climate projection / seasonal prediction (2)

- **OGCMs**
  OGCMs are grid models, and may not need radical change of dynamics for petascale computing architectures.
- **Couplers**
  Communication softwares ‘couplers’ would be rather important, they are to be efficient enough for petascale computing architectures.
  (OASIS4, Radler et al. 2010, S-CUP, Yoshimura 2008)

Adaptive Mesh Refinement



Efforts are needed on

- Subgrid-scale parameterization
- Data assimilation (adjoint)
- Computational efficiency, parallelization, time stepping
- Refinement criteria
- Balance, local conservation etc.
- …

see. Weller et al. (2009) BAMS

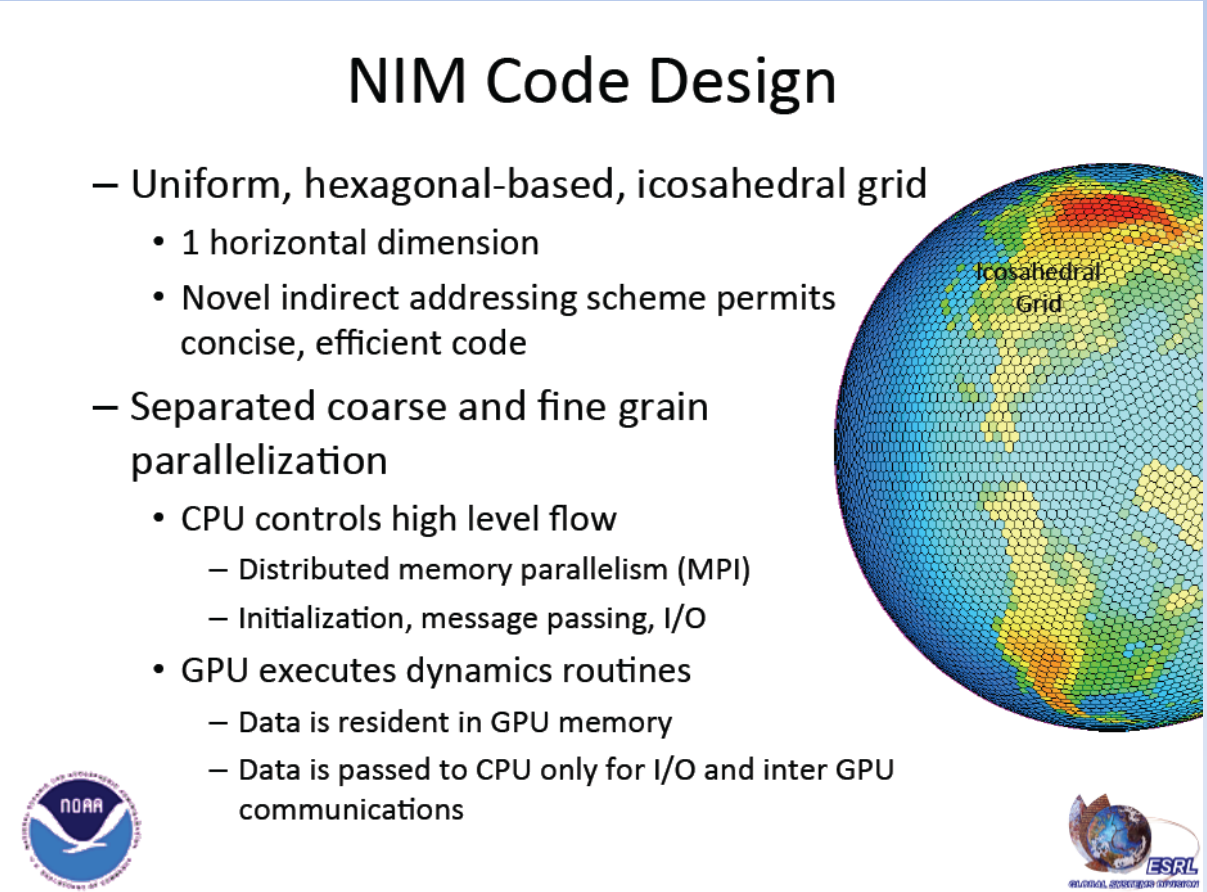
Slingo et al. (2009)
Phil. Trans. R. Soc. A

From Ringler et al. (2011) MWR

Future generation models for climate projection / seasonal prediction

- GPU parallel computing for weather, seasonal, climate predictions would be an option.

NOAA ESRL, parallelization of the NIM dynamical core



NIM Code Design

- Uniform, hexagonal-based, icosahedral grid
  - 1 horizontal dimension
  - Novel indirect addressing scheme permits concise, efficient code
- Separated coarse and fine grain parallelization
  - CPU controls high level flow
    - Distributed memory parallelism (MPI)
    - Initialization, message passing, I/O
  - GPU executes dynamics routines
    - Data is resident in GPU memory
    - Data is passed to CPU only for I/O and inter GPU communications

M.Govett, J. Middlecoff, T.Henderson, J.Rosinski, and C.Tierney, 2011
From a presentation at Workshop on Dynamical Cores for Climate Models, 2011, Lecce, Italy

Summary

Resolution required to resolve each process

Phenomena	Horizontal Scales	Ocean Model Res.	Atmosphere Model Res.
Meso-scale eddies in midlatitudes	~O(100) km	< 25 km (~10km)	< 50 km (<~25 km)
Tropical Instability Waves	~O(1000) km	< 50 km	<100 km (<~50 km)
Western Boundary Currents	~O(100) km	<25 km (~10 km)	< 50 km (<~25 km)

Summary

- Now climate models are going toward ocean eddies and weather resolving models.
- A lot of studies corroborate the advantage of high-resolution models in weather to climate time-scales.
- Some deficiencies may be ameliorated with some parameterizations or computationally-efficient tactics.
- The role of increasing model resolution in improving intra-seasonal to seasonal forecasts should continue to be explored considering available options.

Thank you for your kind attention.

With the advent of more powerful computers, it is now possible, for the first time, to model key processes and phenomena at the resolved scale over large domains, thus enabling multiscale interactions to be explored through the use of computational ‘laboratories’.

Slingo et al. (2009)

Coupled climate system models in which the ocean component is eddy-resolving are on the horizon.

Bryan et al. (2010)