Tropical Cyclone – Ocean Interaction: from Weather, Climate, to Global Warming

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(Many thanks to team members and collaborators...)

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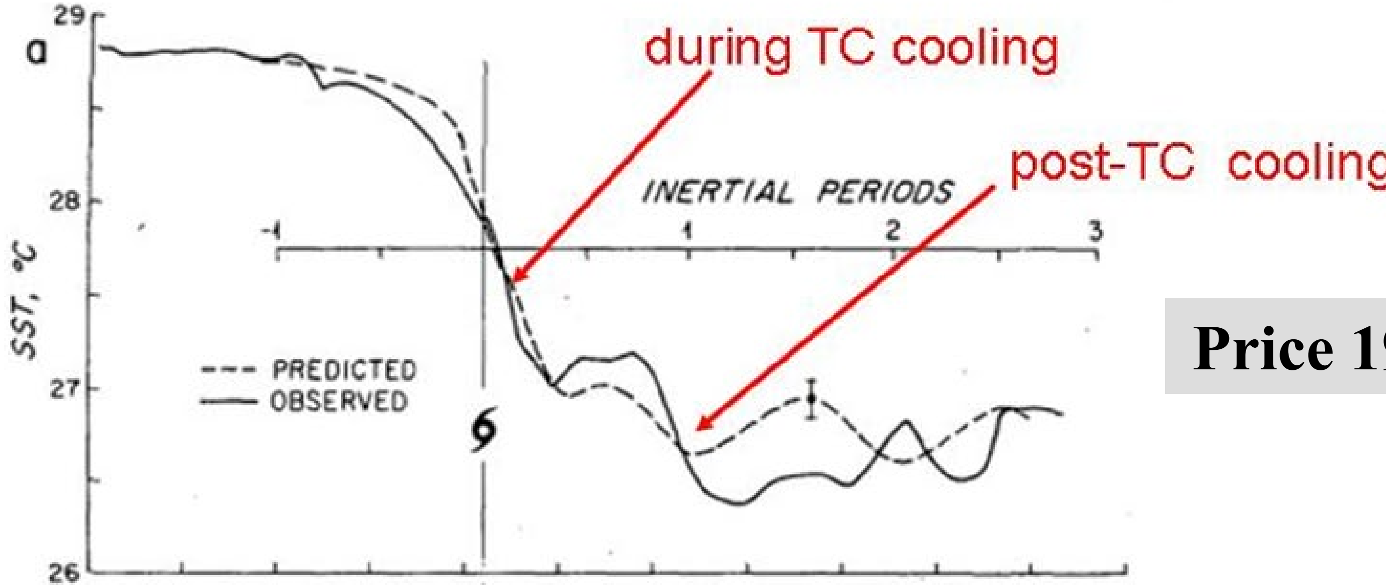


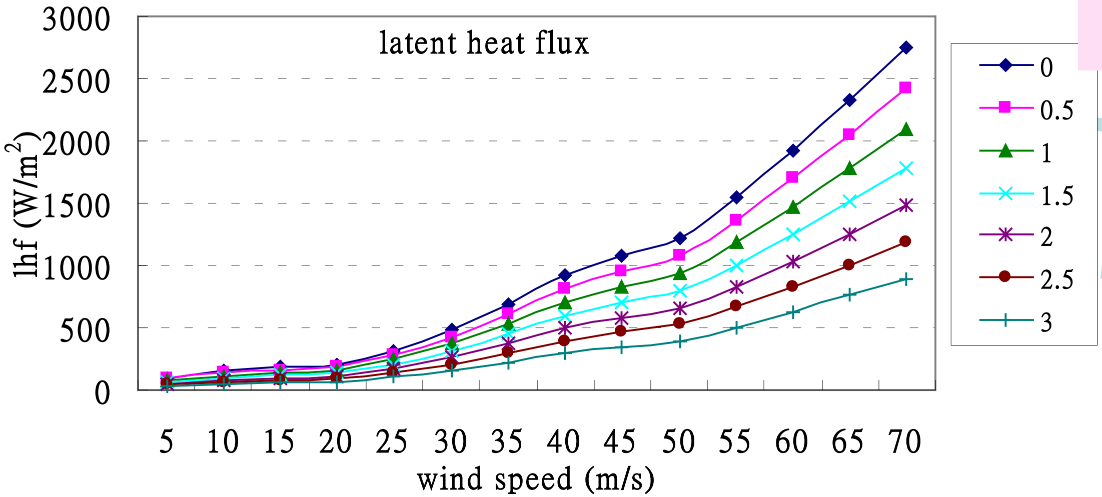
Price 1981

Fundamentals:

1. **TC- Ocean Subsurface Interaction**
2. **TC to Ocean, Ocean to TC, Feedback to Climate/Carbon Cycle**
3. **Pre TC, During TC, Post TC**
4. **Pre TC: Pre TC (SST, OHC, T/S Profiles)**
5. **During TC: TC_Ocean Coupling SST (Tmix),**
   Air-Sea sensible & latent heat flux
   *** Coupled SST=Pre_TC SST – Cooling**
   [cooling depends on Pre_TC Ocean condition & TC attributes (intensity, Uh, and size)]
6. **Post TC cold wake**

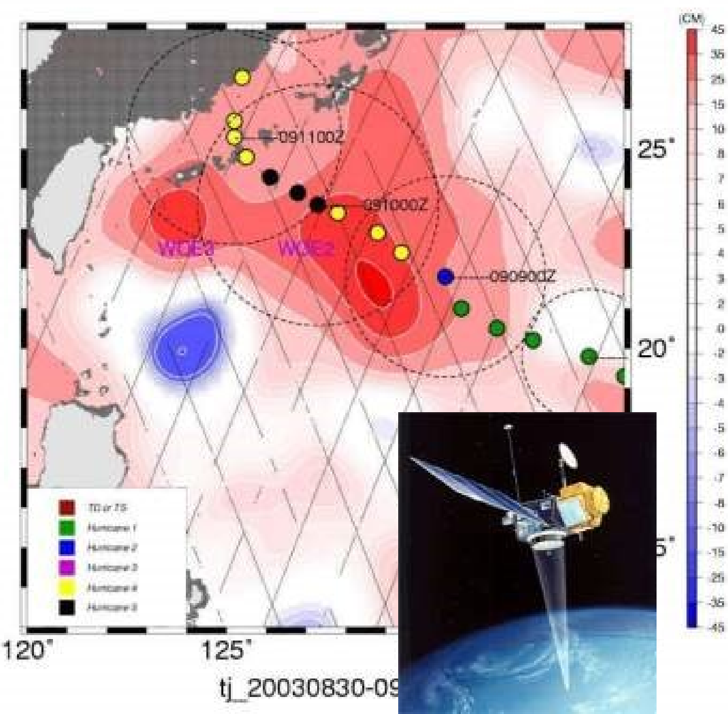
No brake, but accelerator

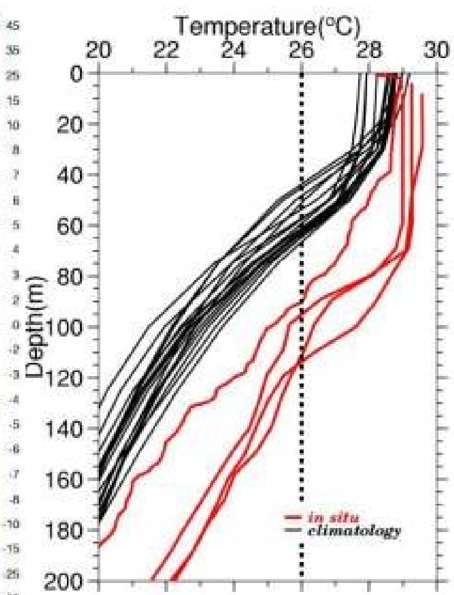
只有油門沒有剎車,只好暴衝!



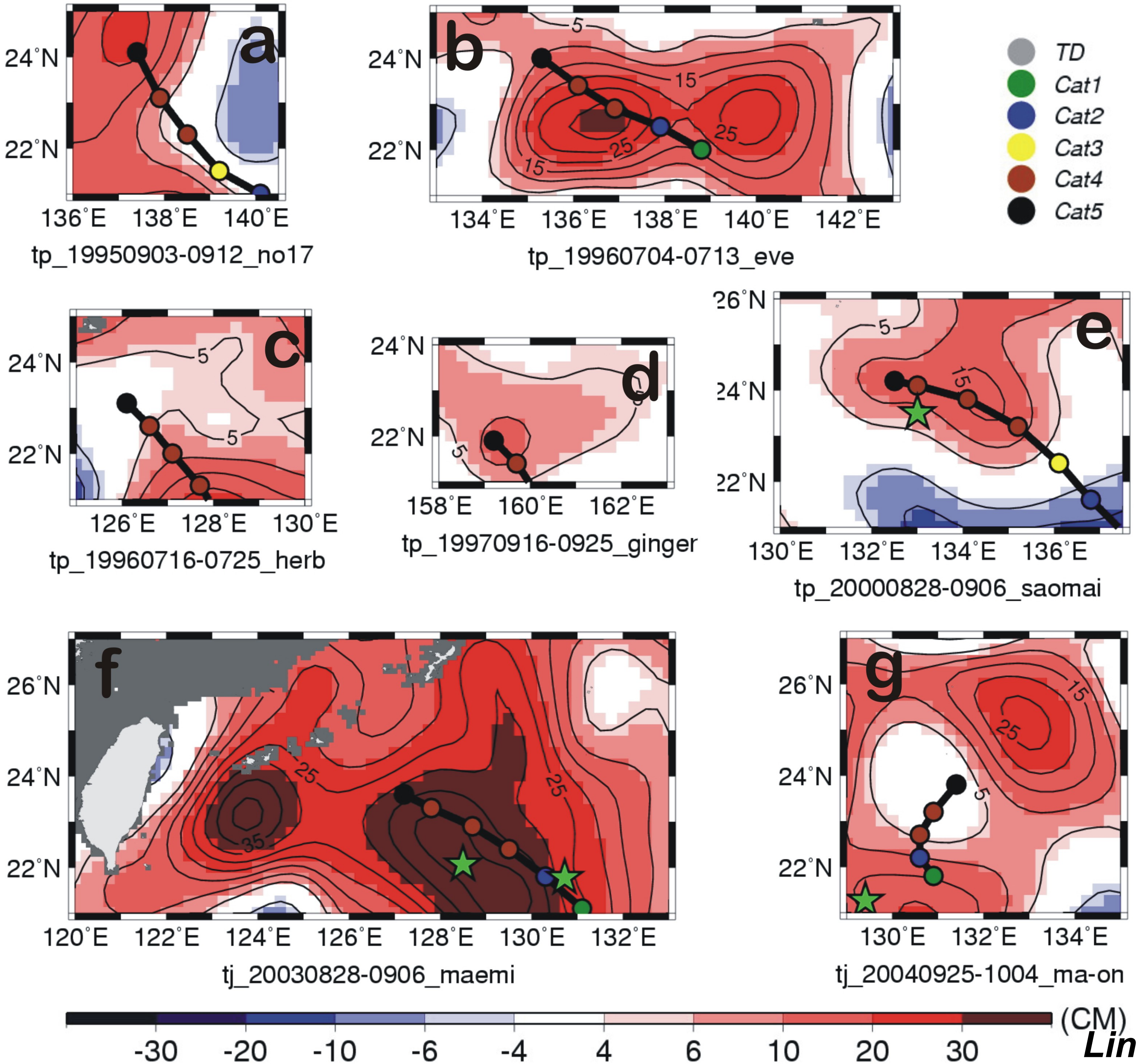
Warm Ocean Eddy (WOE)

RI (Rapid Intensification





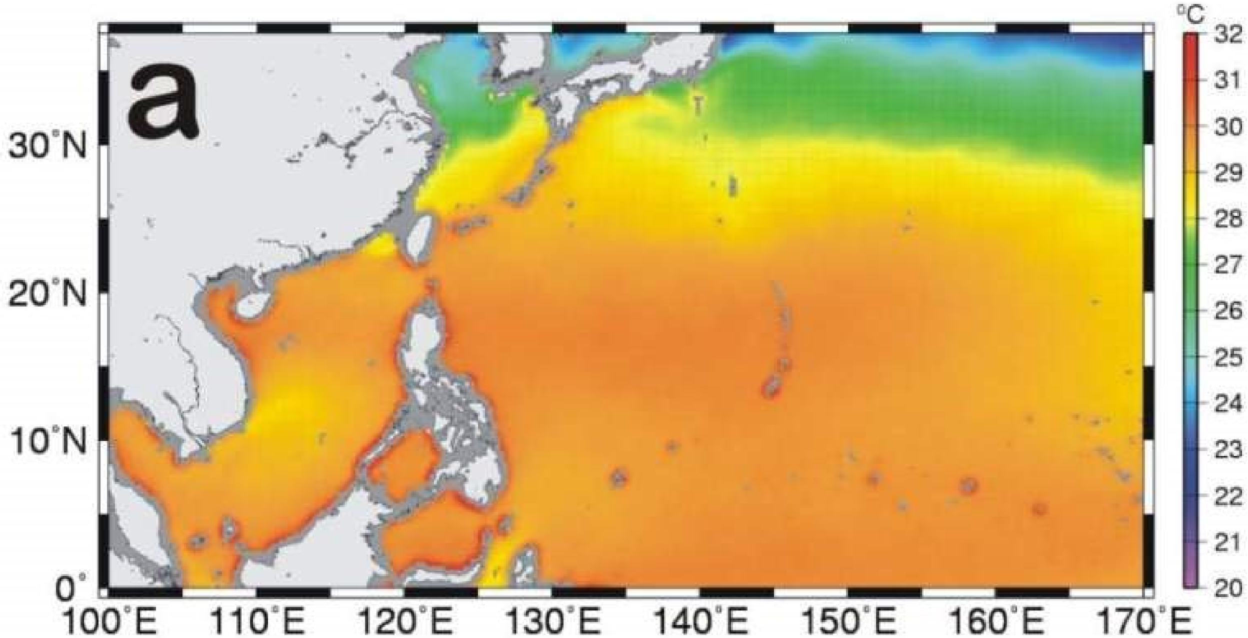
Lin et al. MWR 2005

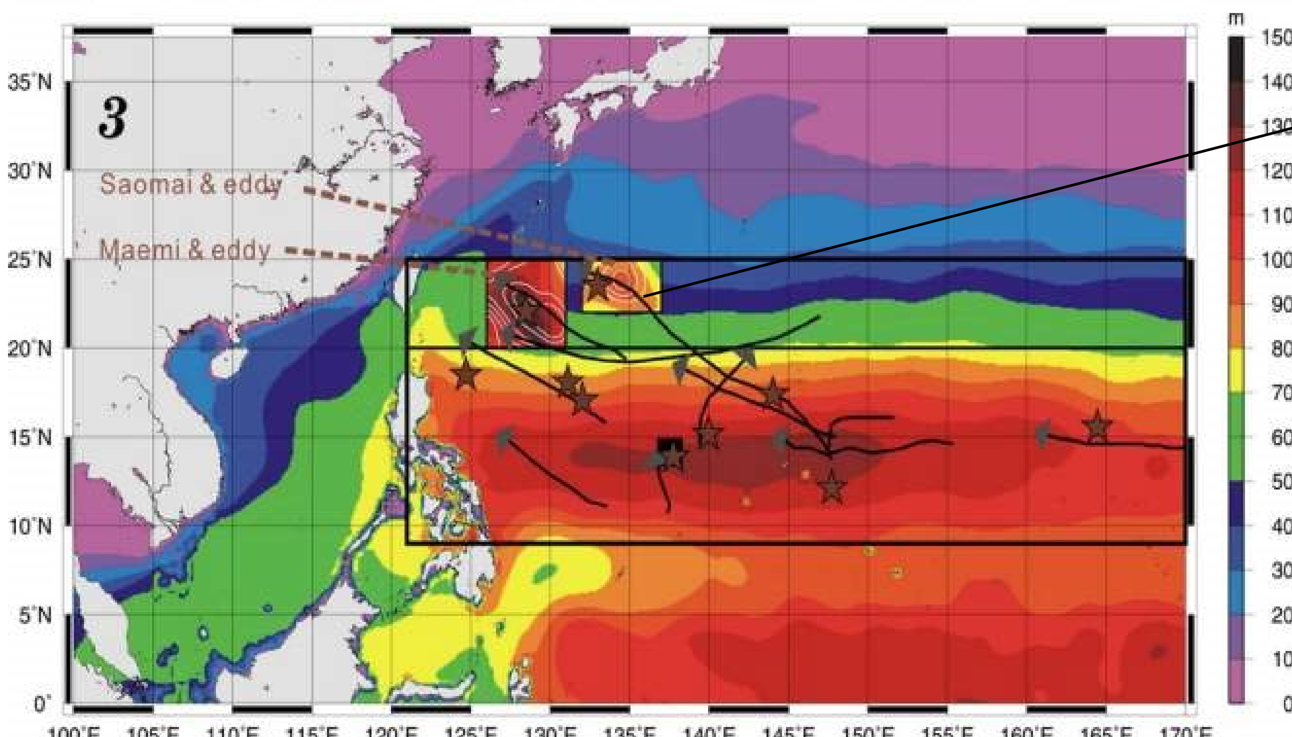


20-26° N

13 yrs of Cat. 5 TCs

Lin et al. MWR 2008





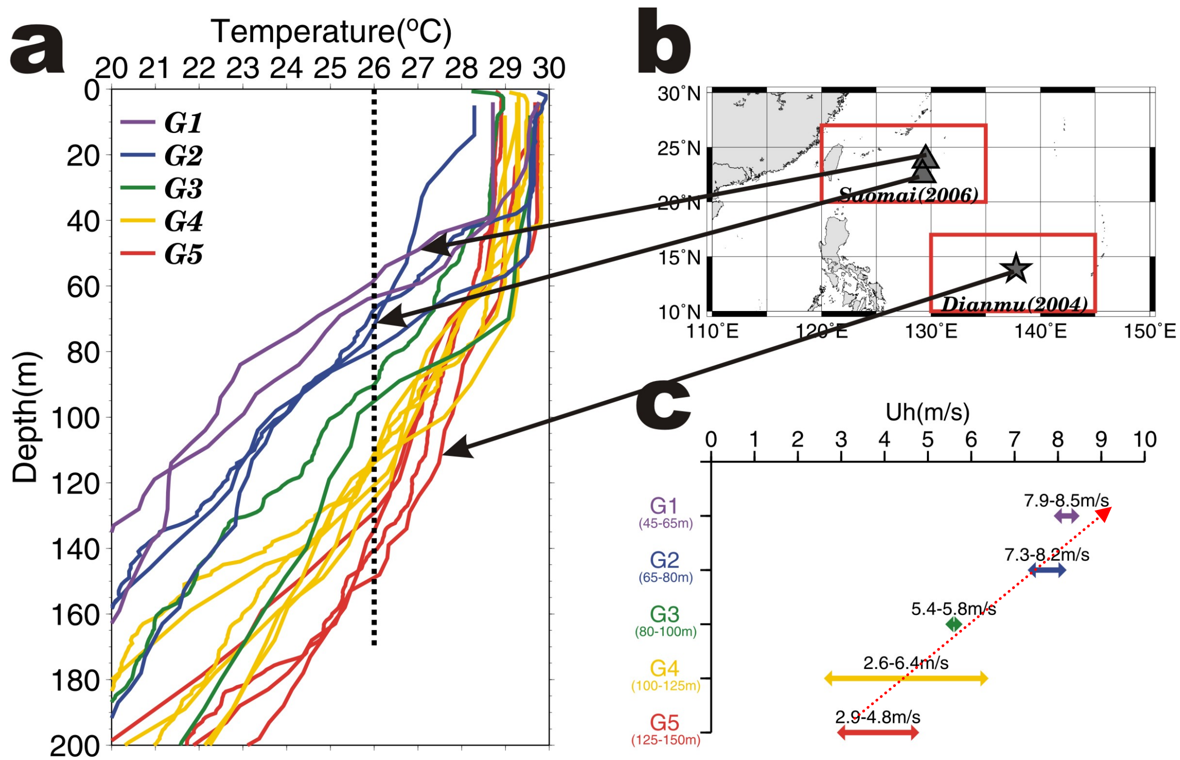
Eddy-rich zone

Lin et al. MWR 2008

10-year of Cat.-5 typhoons

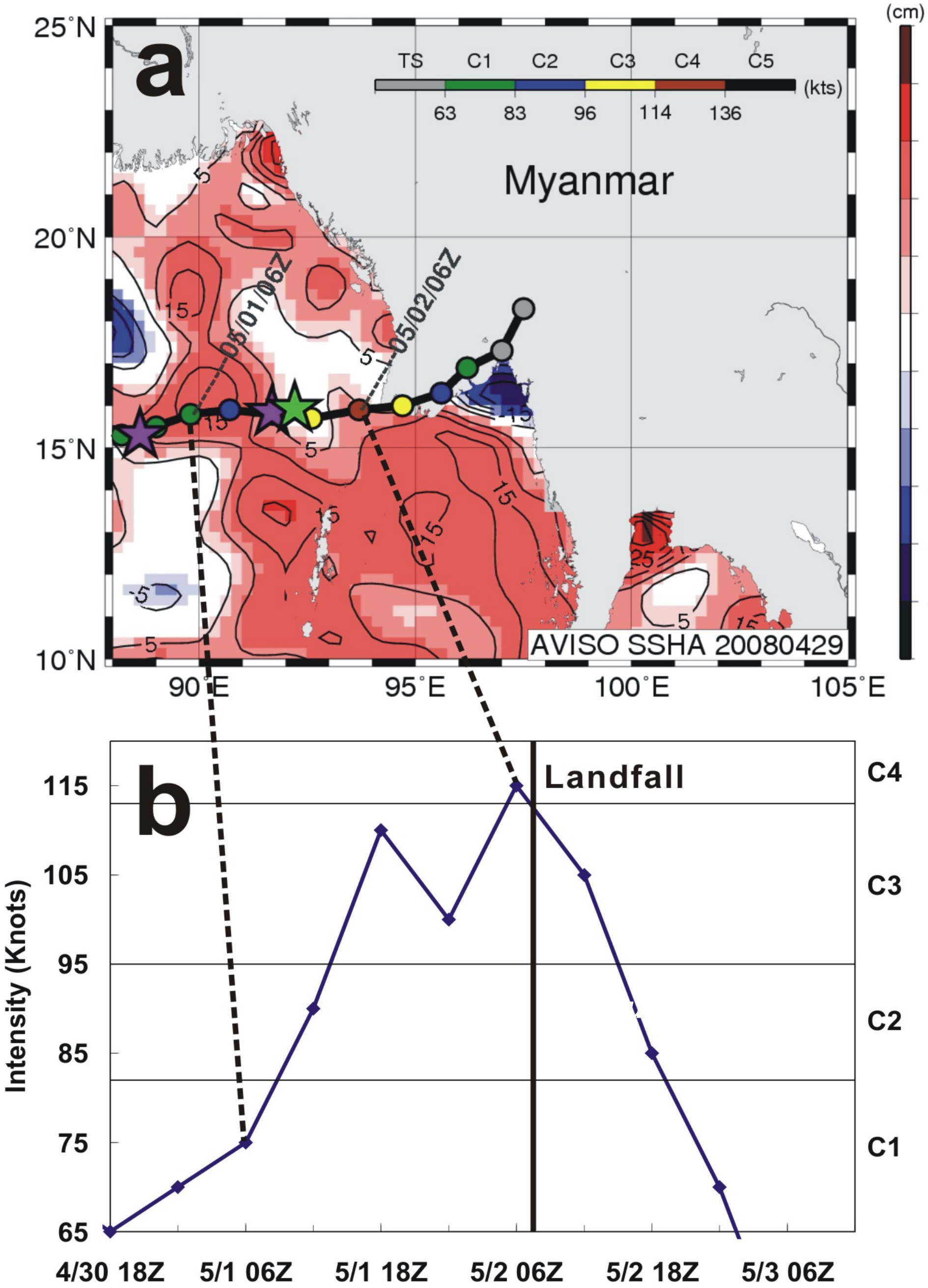
Why some Cat. 5 Intensify over low UOHC region?

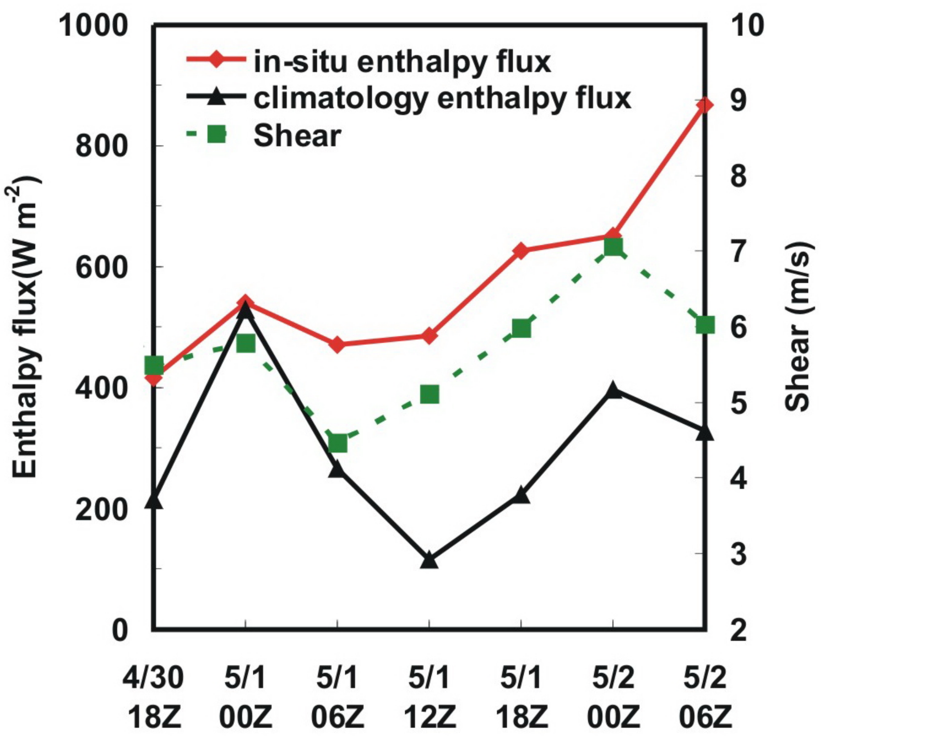
Lin et al. MWR 2009



	pre-SST(℃)	D26(m)	UOHC (kJ/cm^2)	Ave. U_h	Min. U_h	Max. U_h
G1	29.3(0.8)	61(4)	64(15)	8.2(0.4)	7.9	8.5
G2	29.2(0.8)	73(6)	71 (31)	7.8(0.5)	7.3	8.2
G3	28.9(1.0)	93(4)	96 (32)	5.6(0.3)	5.4	5.8
G4	29.3(0.3)	116(5)	117 (10)	4.5(1.4)	3.3	6.4
G5	29.3(0.5)	138(9)	122 (18)	4.1(0.9)	2.9	4.8

Killer cyclone Nargis (2008)





Catastrophic event (> 130,000 death toll):

RI took place just prior to landfall

Lin et al.

GRL 2009

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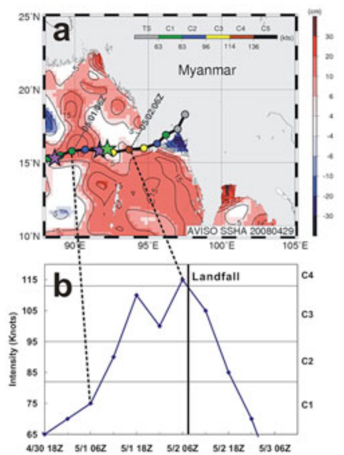
THE Cutting Edge Newly published JPL research

Seeds of disaster

03.19.09



+ Larger image

Cyclone Nargis' rapid growth, as a result of pre-heated water in the nearby ocean. Copyright 2009 American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.

On May 2, 2008, Cyclone Nargis caused the worst natural disaster in the history of Myanmar, a country in Southeast Asia that is more commonly known as Burma. Over 130,000 people were killed and, according to United Nations estimates, 1.5 million people were severely affected. More than $10 billion of damage was done.

One of the things that made Nargis so deadly was the way in which it intensified so quickly before making landfall -- from a category-1 to a category-4 tropical cyclone in just 24 hours. But how exactly did this happen? New research suggests that abnormally warm waters off the coast of Burma in the Bay of Bengal played a major role.

Working alongside researchers in Taiwan, W. Timothy Liu of NASA's Jet Propulsion Laboratory in Pasadena, Calif., analyzed ocean depth and temperature readings that had been collected by floating devices at sea and by satellites such as NASA's Jason-1 ocean surface topography mapper. They found that, around the time of the cyclone, the waters near Burma contained an unusually warm layer 100 to 200 meters (about 109 to 219 yards) deep. The extra energy in this layer meant that the atmosphere above the ocean was "fed" with three times as much heat, enabling Cyclone Nargis to intensify so rapidly.

Research from:

Jason-1

• Jason-1 home page

While the Burma tragedy cannot be undone, Liu and colleagues hope that the work will help to improve forecasts of future cyclones in the Northern Indian Ocean, which are notoriously hard to predict.

The results appear in Geophysical Research Letters.

Research paper:
- Warm ocean anomaly, air sea fluxes, and the rapid intensification of tropical cyclone Nargis (2008)

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NASA Study Finds 'Pre-Existi Condition' Fueled Killer Cyclo

ScienceDaily (Mar. 2, 2009) A "pre-existing condition" in the North Indian intensification of last year's Tropical Cyclone Nargis just before its devast according to a new NASA/university study. The

nglish.ScienceWeek - Study Finds 'Pre-Existing Condition' Fueled Killer Cyclone - M

http://english.scienceweek.cz/headlines/id/94344

Pre-existing Nargis NASA

ScienceWeek
The latest News Headlines from the Sci

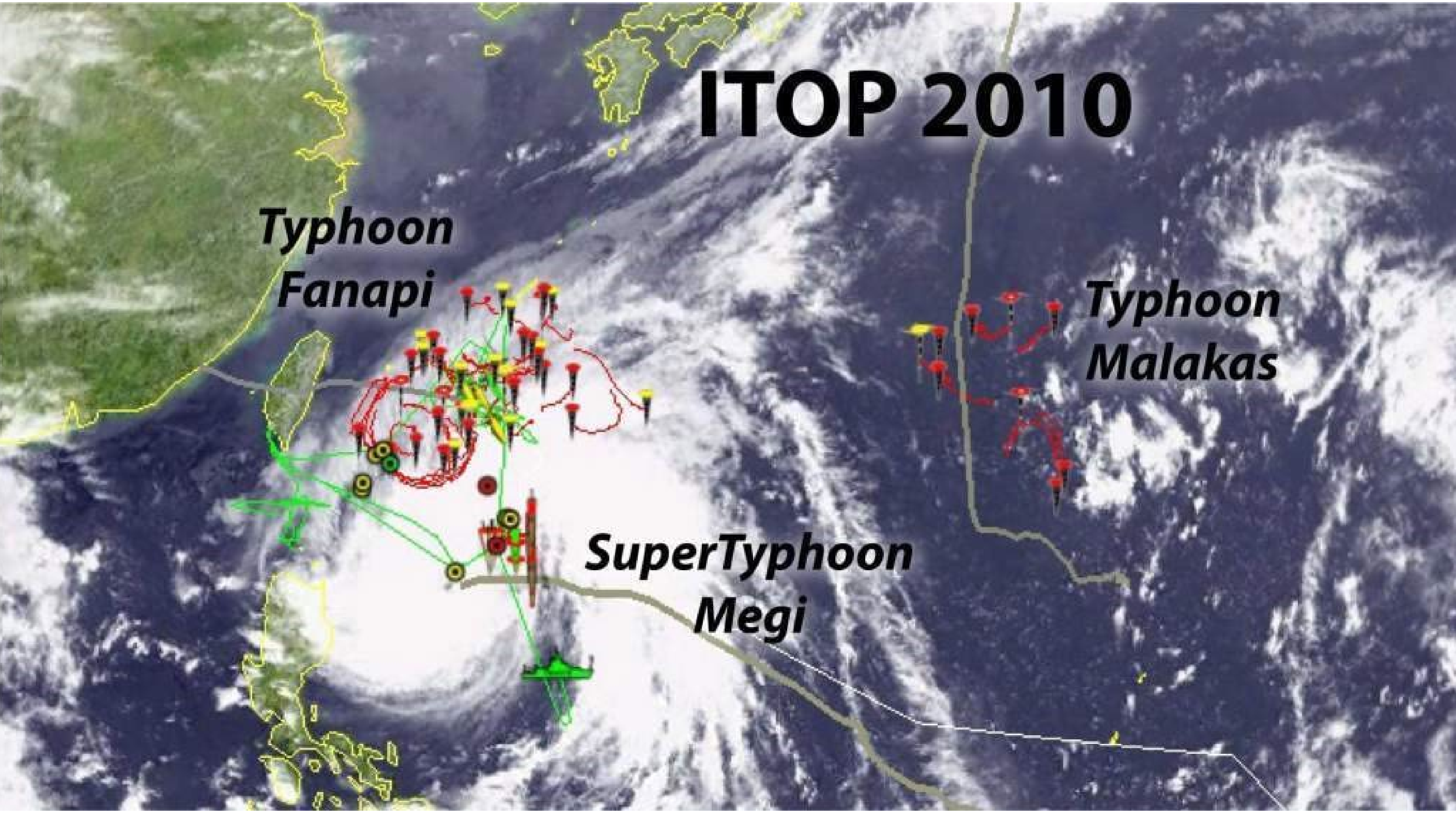
Study Finds 'Pre-Existing

26. 2 2009 (23:40)

(PhysOrg.com) -- A "pre-existing condit sudden intensification of last year's Trop landfall in Burma, according to a new N Burma's worst natural disaster ever and

Read the story at PhysOrg

Case 1: Supertyphoon Megi: Cat 5:160 kts , 12 Z 17 Oct. 2010)

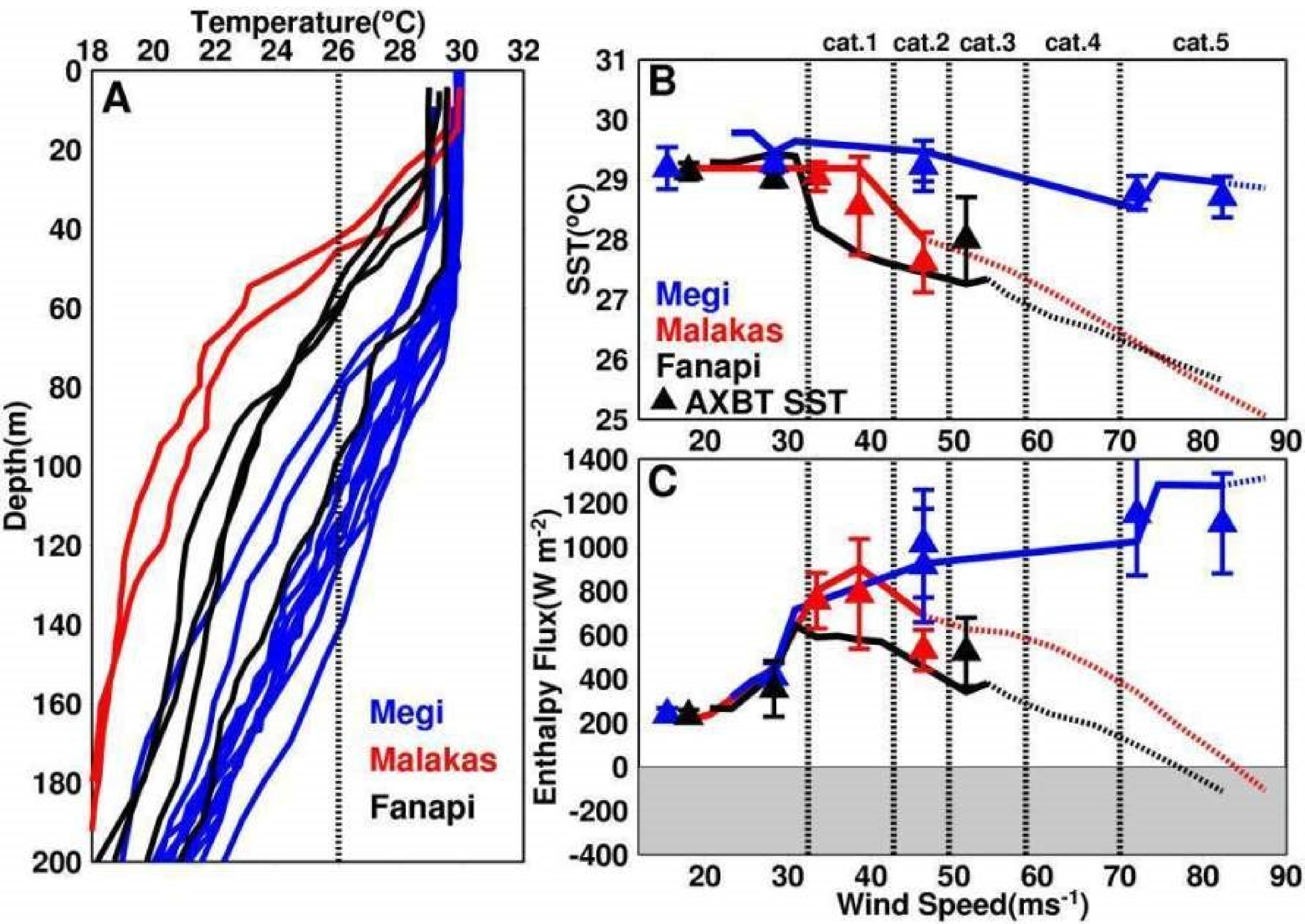


Case 2: Typhoon Malakas: Cat2: 90 kts on 24 Sep. 2010

Case 3: Typhoon Fanapi: Cat 3: 105 kts on 18 Sep. 2010

C130 Airdrop

(From Steve Jayne/WHOI and Eric D'Asaro/U. of Washington)



Temperature(°C)
18 20 22 24 26 28 30 32
A
Depth(m)
0 20 40 60 80 100 120 140 160 180 200
Megi
Malakas
Fanapi
cat.1 cat.2 cat.3 cat.4 cat.5
B
SST(°C)
31 30 29 28 27 26 25
Megi
Malakas
Fanapi
AXBT SST
20 30 40 50 60 70 80 90
C
Enthalpy Flux(W m^{-2})
1400 1200 1000 800 600 400 200 0 -200 -400
Wind Speed(ms^{-1})

Lin GRL 2013

Ocean Coupling Potential Intensity (OCPI)

Include subsurface info. in PI

$$V^2 = \frac{SST - T_0}{T_0} \frac{C_k}{C_D} (k^* - k)$$

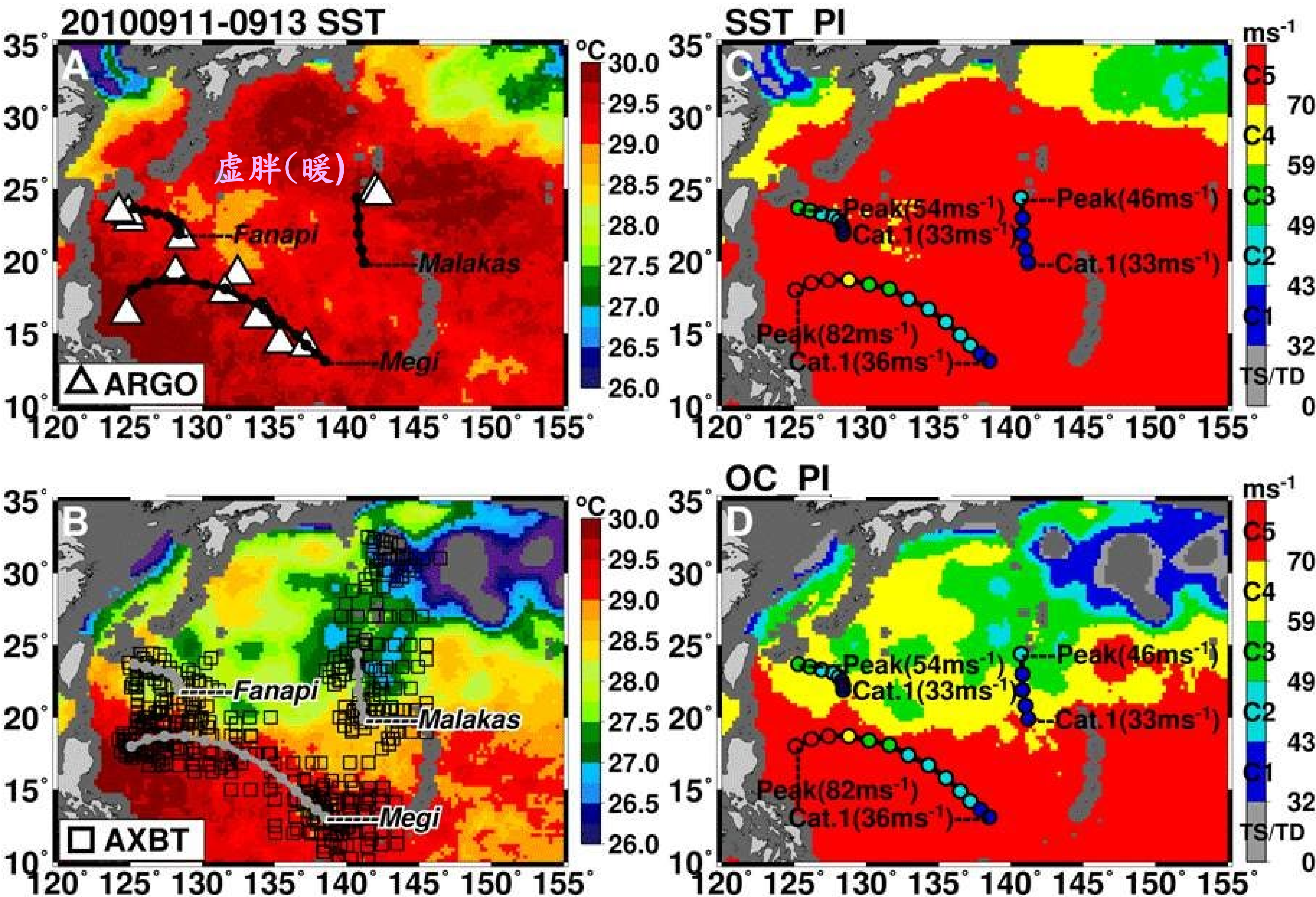
Emanuel 1988; Bister and Emanuel 1998

Pre SST

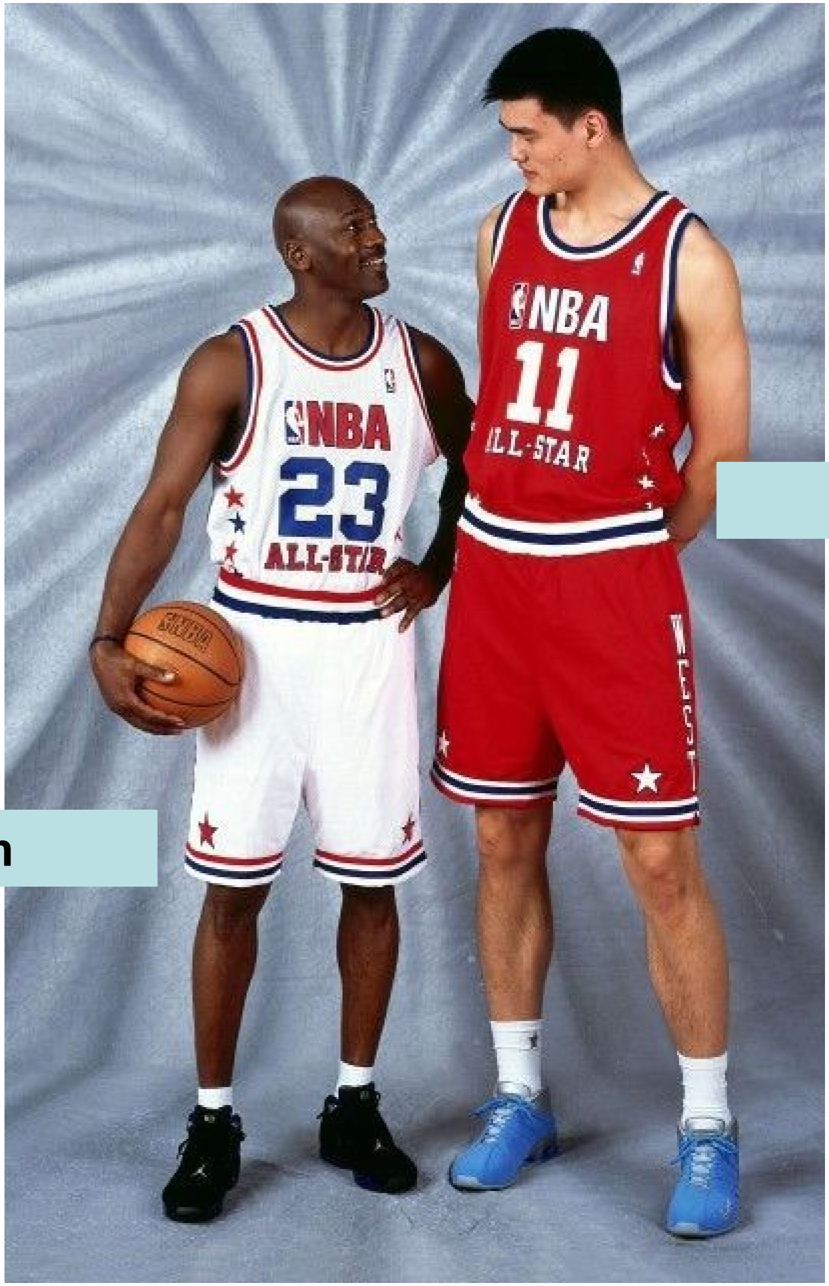
$$V_{OC\_PI}{}^2 = \frac{\bar{T} - T_0}{T_0} \frac{C_k}{C_D} (k^* - k)$$

Predicted Tmix (Price 2009), If for quick choice, use T80

Lin GRL 2013



Lin et al. GRL 2013; Weather / Climate Applications



2.29m

1.98m

The Economist

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Cat. '6', Haiyan: 170kts!

Typhoon Haiyan

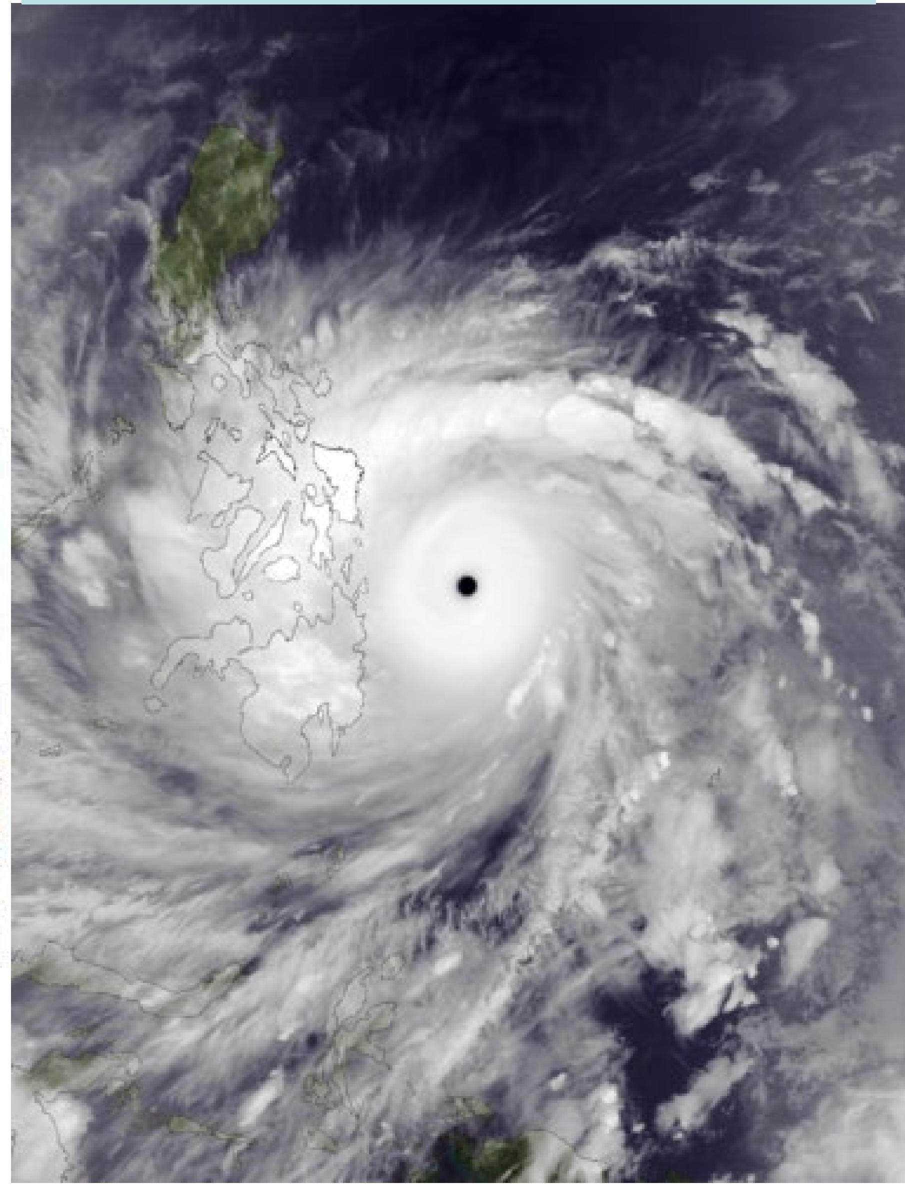
Print edition

Worse than hell

One of the strongest storms ever recorded has devastated parts of the Philippines, and relief is slow to arrive

Nov 16th 2013 | CEBU, HANOI AND MANILA | From the print edition

Timekeeper | Like 33 | Tweet 37



Death: 6300; Injured: 28689;

Damage : US $ 2,051,710,653 (2 billion)

http://en.wikipedia.org/wiki/Typhoon_Haiyan

Haiyan (170kts) – Category ‘6’& at landfall, Lin et al. GRL 2014

Category	Winds (knots)	V^2 (fcn. of ACE, k. energy)	V^3 (fcn. of PDI, destructiveness)
1	64-82	4,096	262,144
2	83-95	6,889	571,787
3	96-113	9,216	884,736
4	114-135	12,996	1,481,544
5 (Katrina)	>135 - 159	18,225	2,460,375
‘Cat 6’?	**>=160 (160-170-185)**	**25,600-28,900-34,225**	**4,096,000-4,913,000-6,331,625**

19

13

18

22

25

x1.7

x1.3

x1.4

x1.4

x1.5-1.6-1.9

x2.2

x1.5

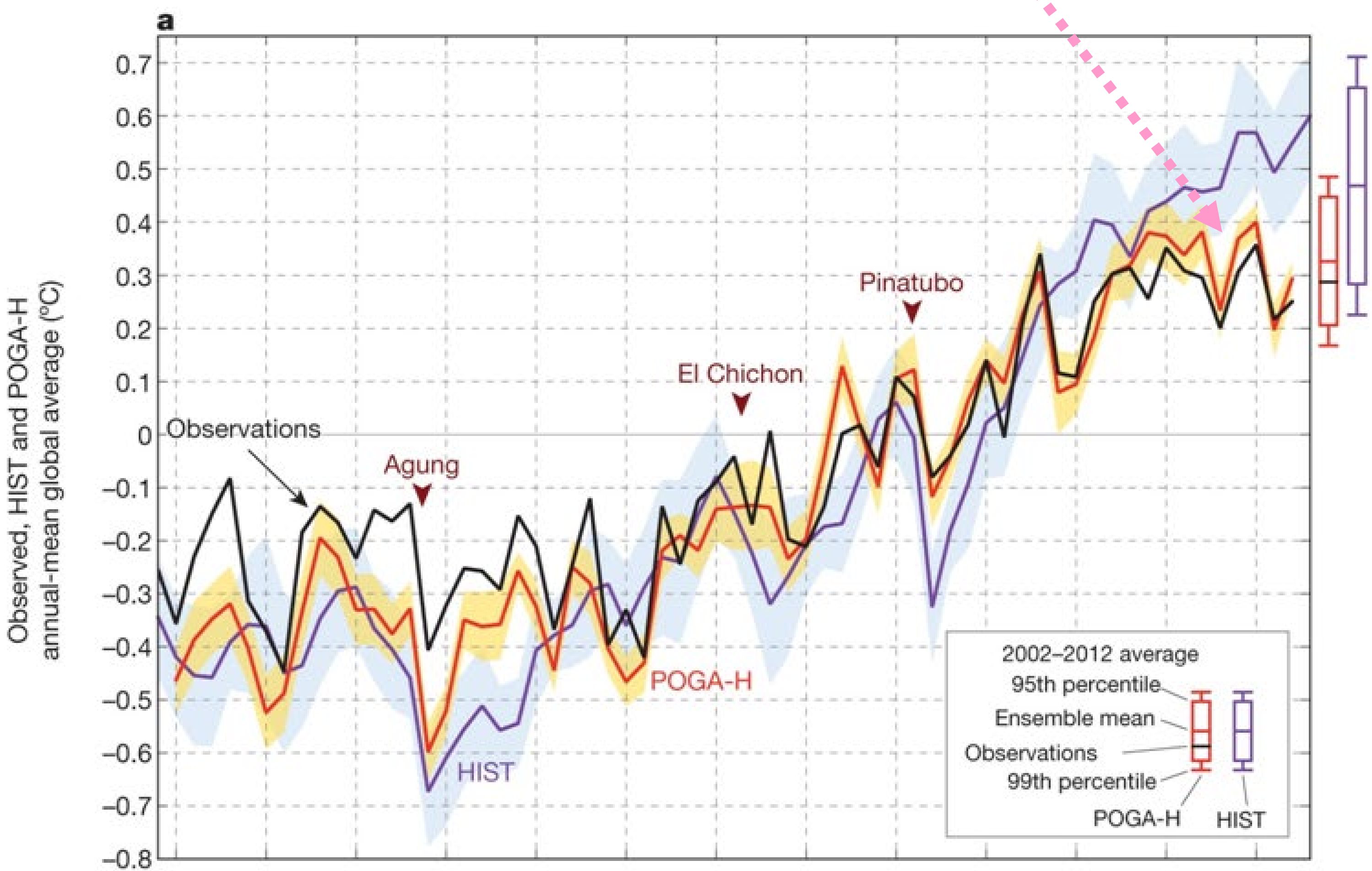
x1.7

x1.7

x1.8-2.0-2.6

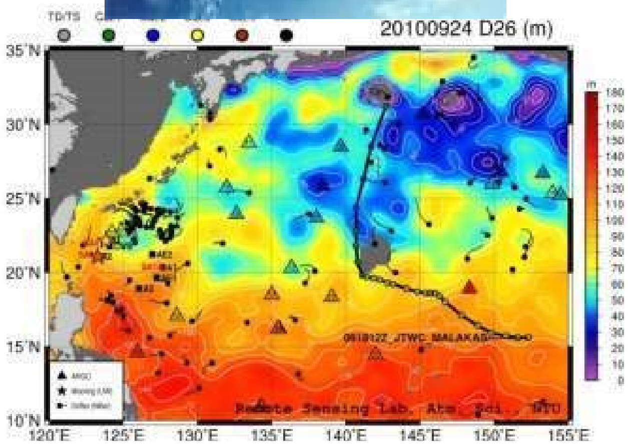
Haiyan from Global warming ?

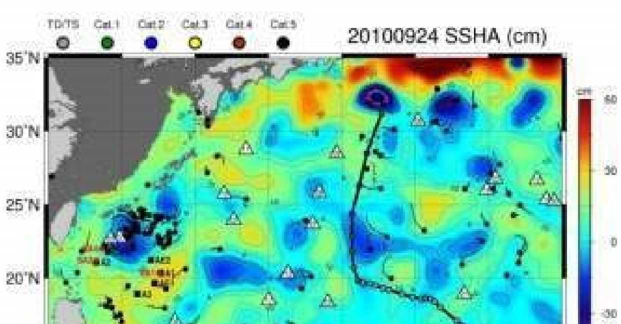
But …it is Hiatus!

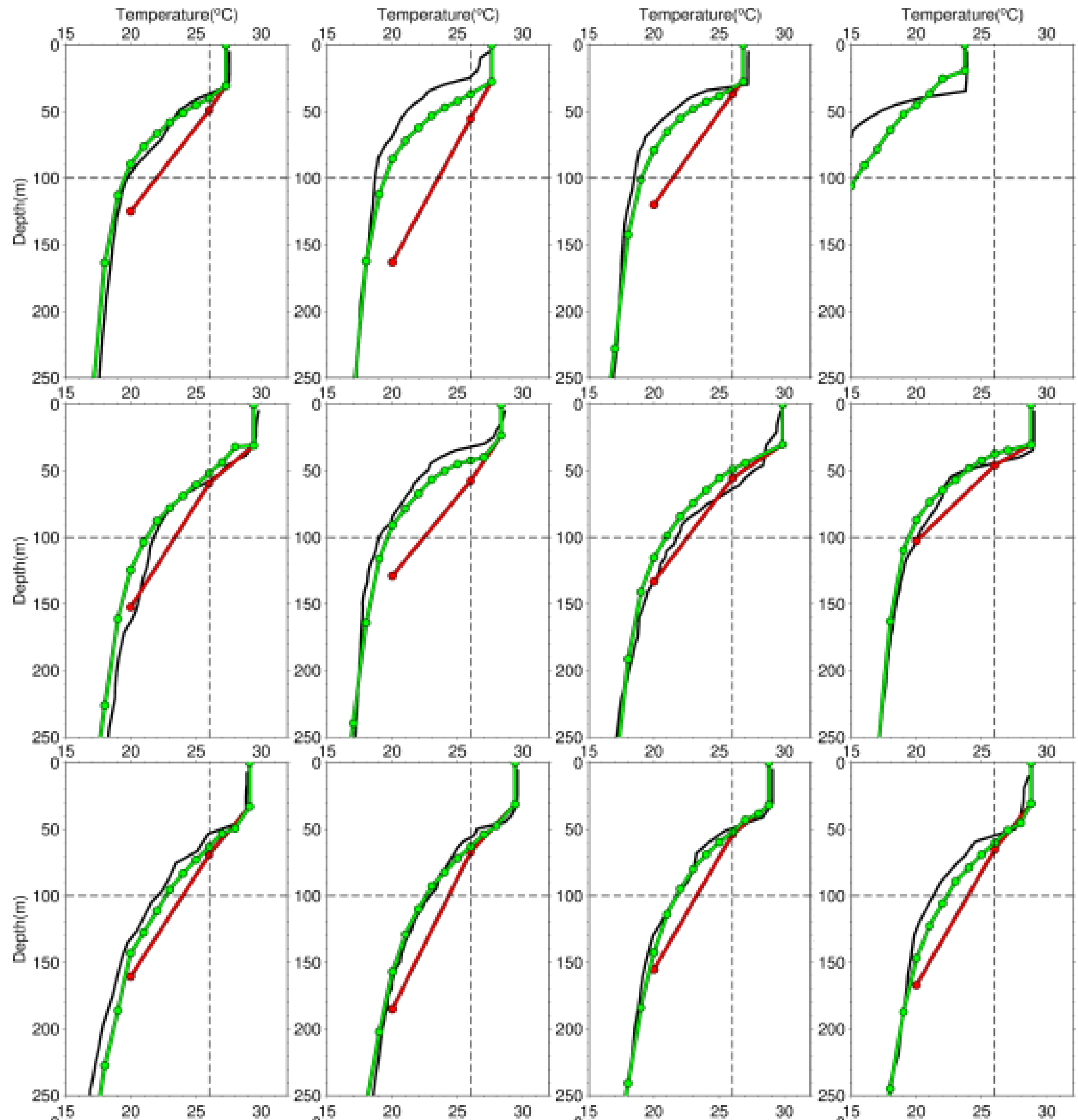


Kosaka and Xie, Nature 2013

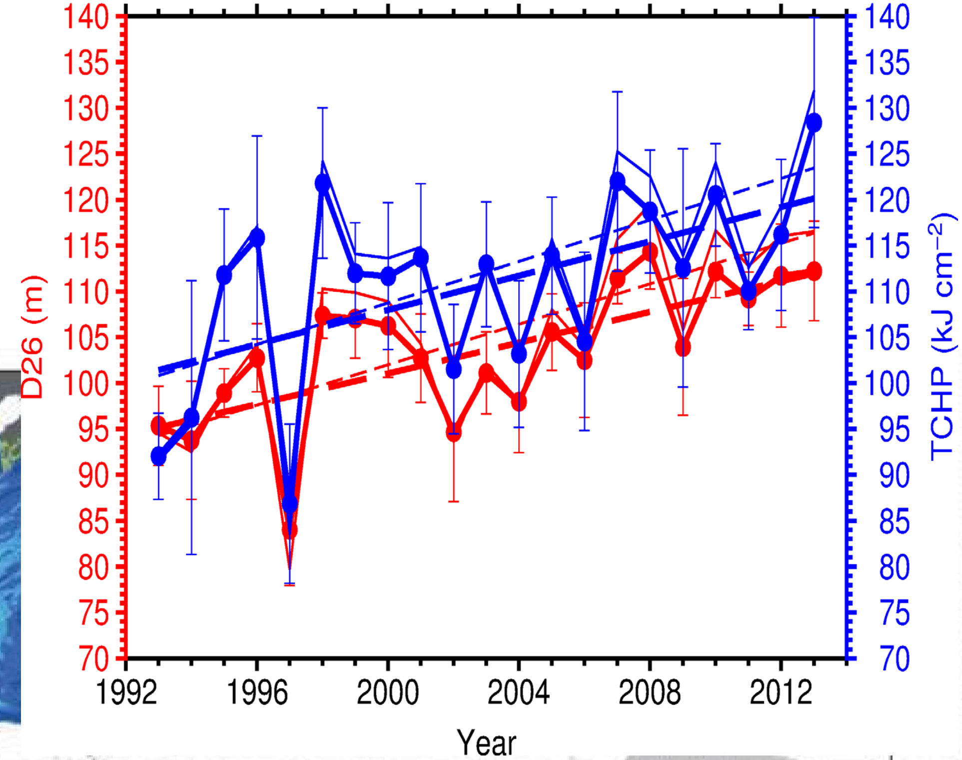
Argo is not enough, because each grid needs a profile operationally (Pun et al. Prg. Ocean. 2014)







Pun et al. GRL, Sep. 2013



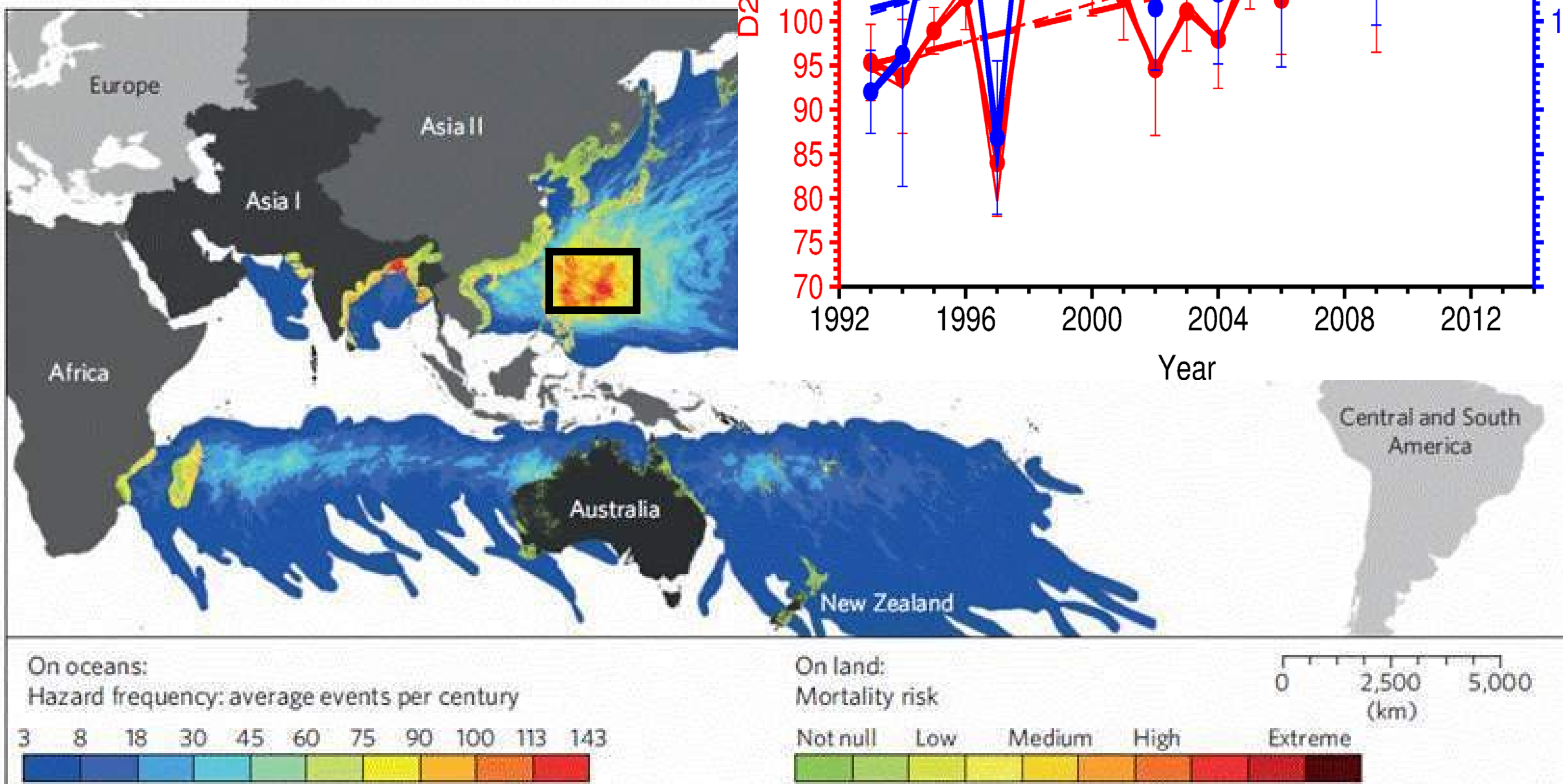
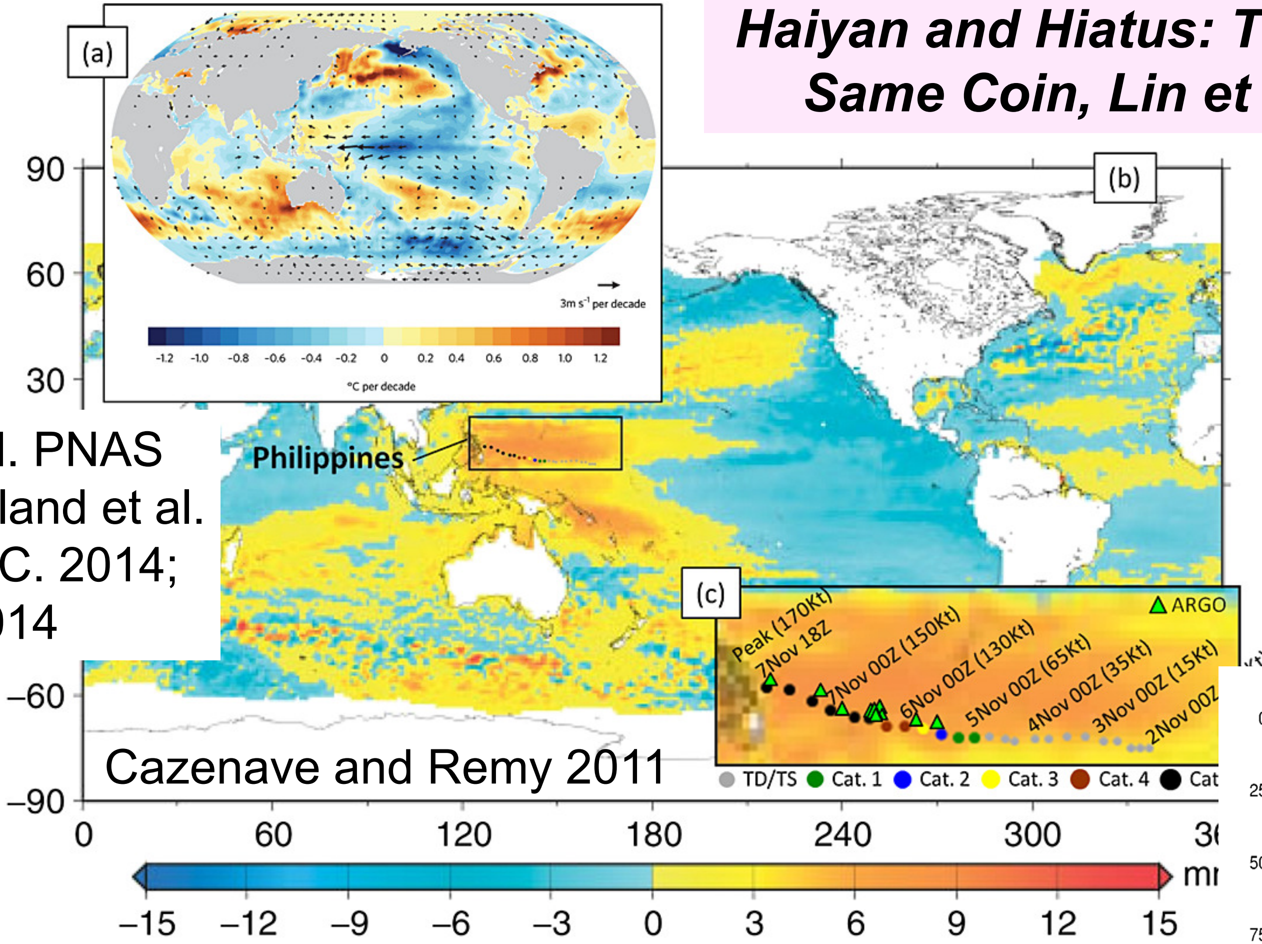


Figure 1 | Map showing distribution of hazard frequency and mortality risk from TCs for the year 2010. Estimates are applied to all pixels on a geographic grid. Mortality risk is categorized from low to extreme.

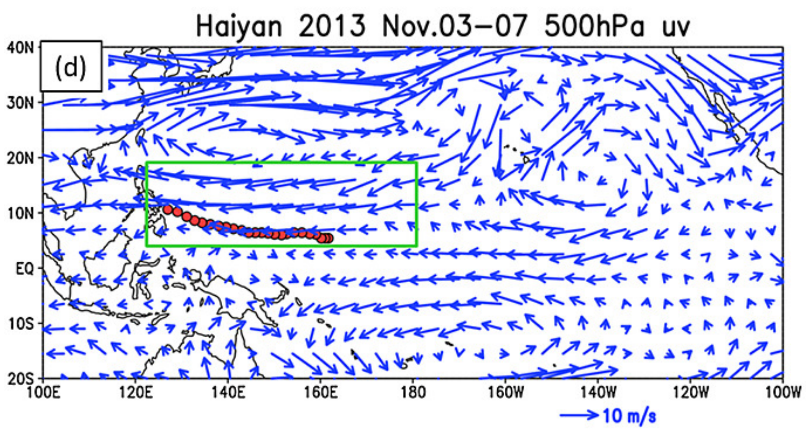
Peduzzi et al. *Nat. C.C.* 2012

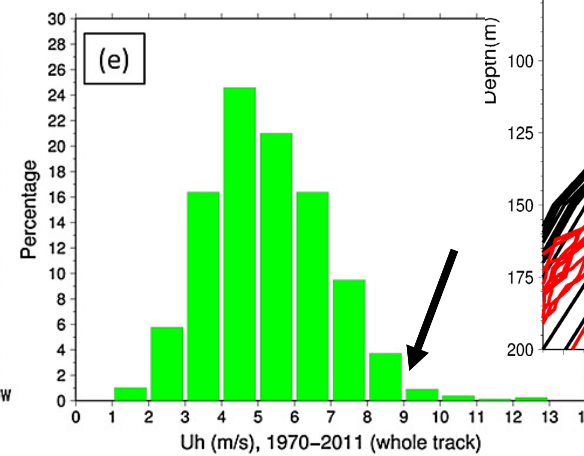
Haiyan and Hiatus: Two Sides of the Same Coin, Lin et al. GRL 2014

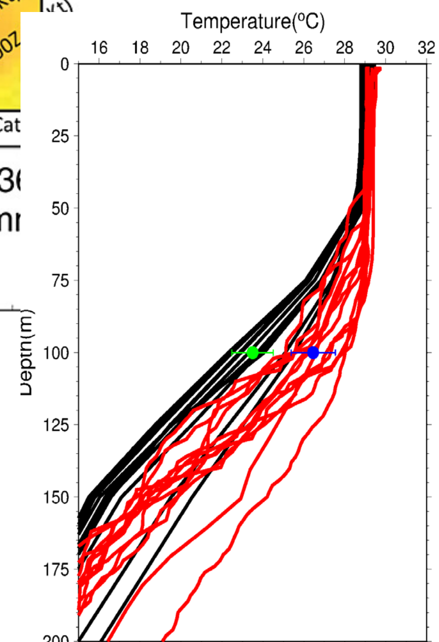


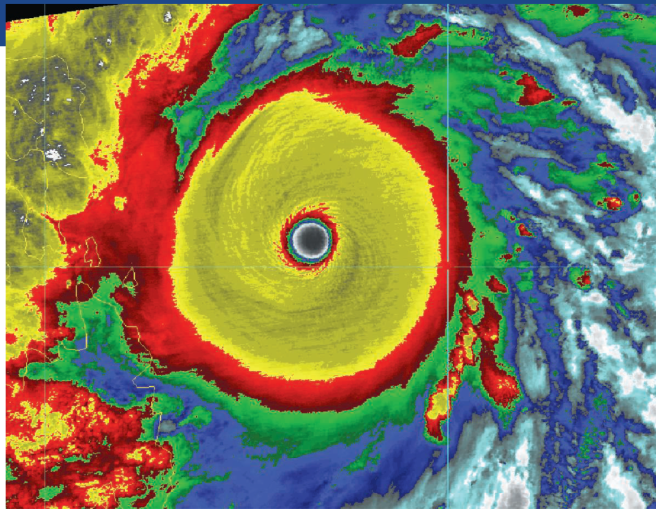
Wang et al. PNAS 2013; England et al. Nature C. C. 2014; Kosaka 2014

Cazenave and Remy 2011









Feeding the monster. Unusually warm Pacific waters supercharged Haiyan.

CREDITS (TOP TO BOTTOM): JOHN KNAFF, NOAA/NESDIS/RAMMB, CSU/CIRA; I-I LIN

CLIMATOLOGY

Clues to Supertyphoon's Ferocity Found in the Western Pacific

Tropical storm watchers agree that Haiyan was probably the strongest typhoon to make landfall when it slammed into the Philippines on 8 November, packing winds of up to 314 kilometers per hour. What gave Haiyan, which killed thousands and displaced millions, its deadly wallop?

Researchers think they have at least a partial answer to that question: unusually warm subsurface Pacific waters east of the Philippines. A related phenomenon—rising sea levels in the western Pacific—likely abetted Haiyan's devastating storm surge, which caused more deaths than the winds themselves.

Typhoons draw heat from the ocean for the energy that generates their winds. Typically, as a storm's winds increase, they stir up deeper, cooler ocean waters that temper its strength. This cooling effect "is nature's brake to stop typhoons from intensifying," says I-I Lin, a specialist in typhoon-ocean interactions at National Taiwan University in Taipei.

Drawing on data from satellite observations and Argo floats—thousands of instrumented, subsurface probes that measure ocean temperature, salinity, and current speeds—Lin and others have documented a steady 2-decade rise in subsurface temperatures in the western North Pacific and a bulging warm water layer. The warmer and thicker that subsurface layer, the more heat is available to feed a storm. Oceanographers use a measure called the Tropical Cyclone Heat Potential (TCHP) to quantify the heat reservoir. Lin and colleague Iam-Fei Pun reported online on 3 September in *Geophysical Research Letters* that the TCHP where most cyclones develop in the western North Pacific has increased 10% since the early 1990s surface waters along only slightly warmer t

康熙盛世

down to 100 meters were 3° warmer than the historical average. So as Haiyan churned up western Pacific waters, it drew more wind-intensifying heat, Lin says.

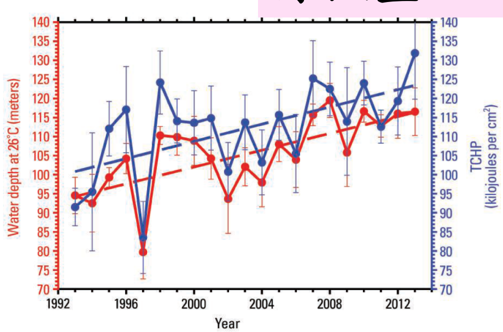
Other factors contributed to Haiyan's intensity. "The genesis location was very important," says Il-Ju Moon, a marine meteorologist at Jeju National University in South Korea who studies how ocean heat influences typhoons. Haiyan originated around 5° latitude north of the equator and was at about 10° when it hit land. "The ocean heat content is very high in that region," Moon says. And starting more than 3000 kilometers east of the Philippines gave Haiyan plenty of open water over which to strengthen.

Haiyan was a speed demon as well. "It was flying over the water" at 32 kilometers per hour, Lin says, nearly twice as fast as most typhoons travel. "Why it moved so fast is unknown," she adds. Researchers speculate that a fast-moving storm passes by before its churn pulls energy-sapping deeper, cooler water to the surface. In any case, "the warmer the subsurface layer, the faster the moving speed, the smaller the cooling effect," Lin says. "It's like a car without a brake, only an accelerator."

The warm bulge in the western North Pacific is the result of stronger easterly trade winds. This phenomenon also aggravated Haiyan's storm surge. In addition to blowing heat westward, the winds are literally piling up water in the western Pacific, where the cumulative sea-level rise over the past ceeds 20 centimeters, says Bo anographer at the University Manoa. "It is likely that the elevated sea level contributed to the flood and inundation problems" in the Philippines, he says.

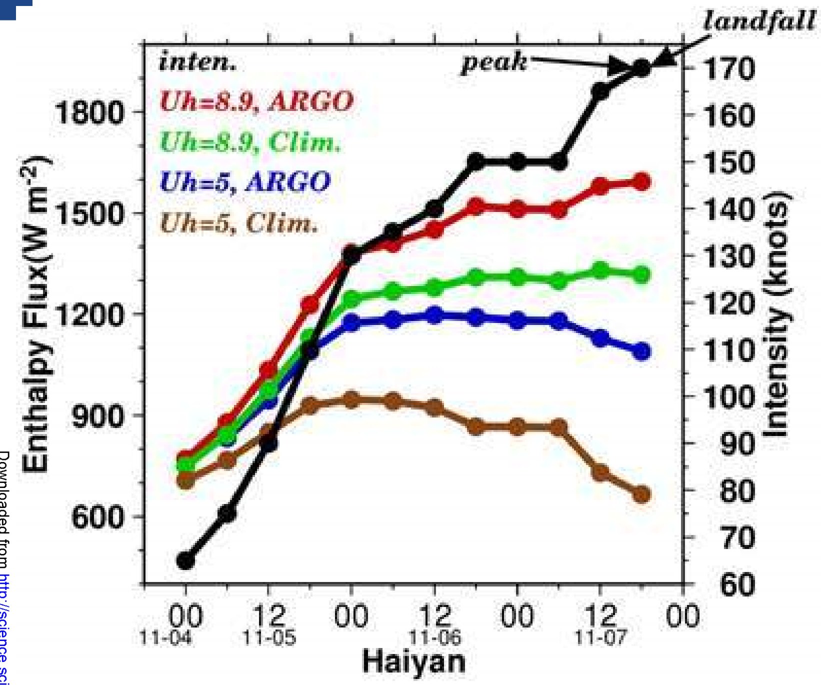
While many observers blame Haiyan's destructive power on climate change, tropical storm experts say there is little hard evidence of a link. "It is possibly natural variability," Lin says. Nor is it certain that the western Pacific has become a supertyphoon breeding ground. Although warmer subsurface waters might raise the risk, Lin says, atmospheric conditions may not always cooperate.

–DENNIS NORMILE

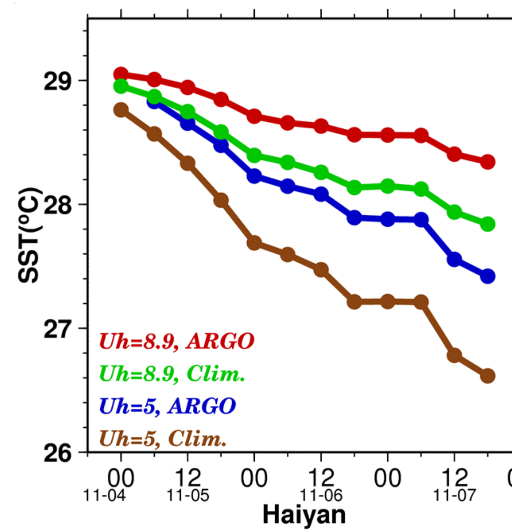


Heated situation. Over 2 decades, a thickening layer of warm water (red) increased the storm-driving heat potential (blue) at the latitudes Haiyan traversed.

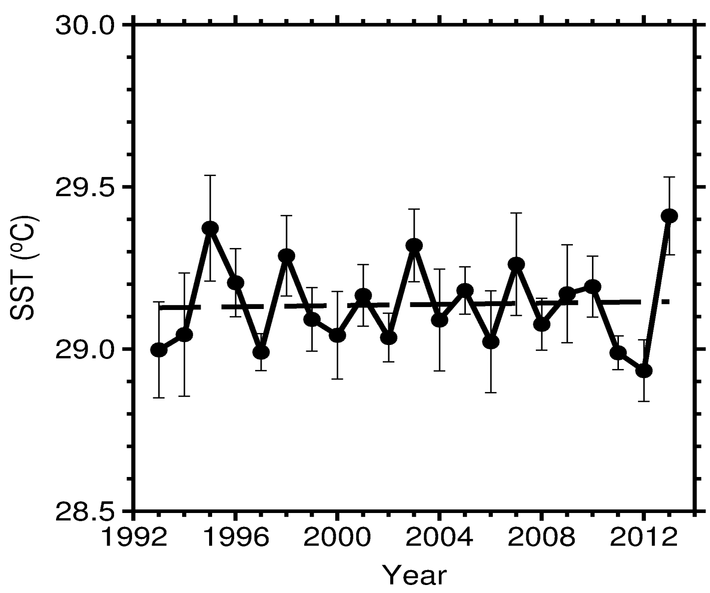
Published by AAAS

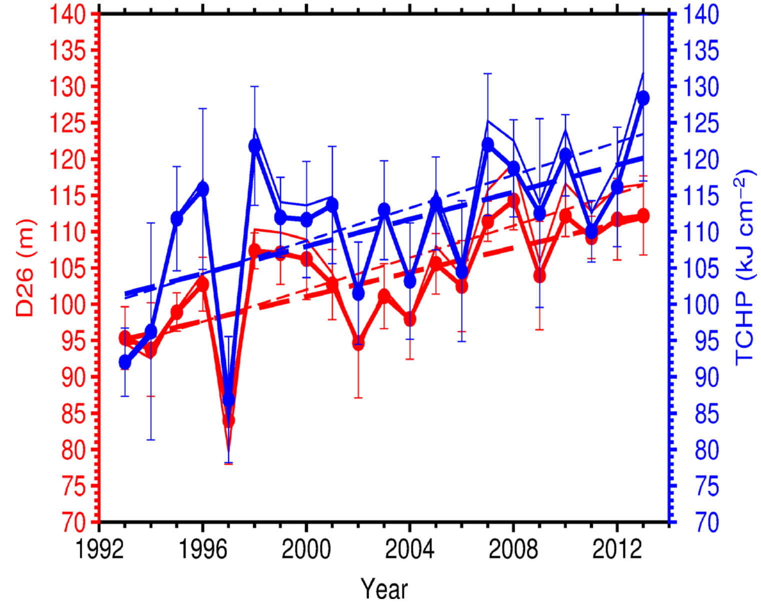


158% more flux supply

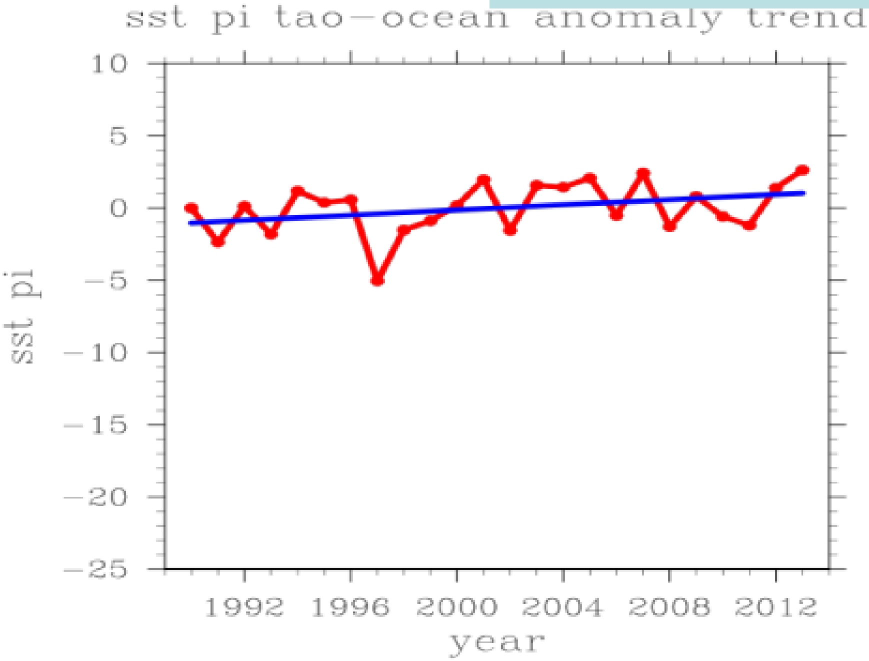


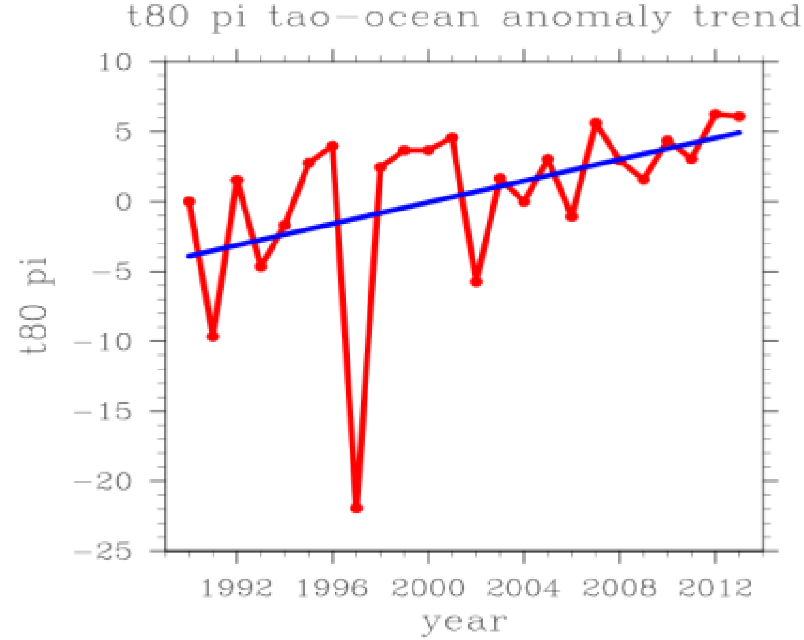
Lin et al. GRL. 2014



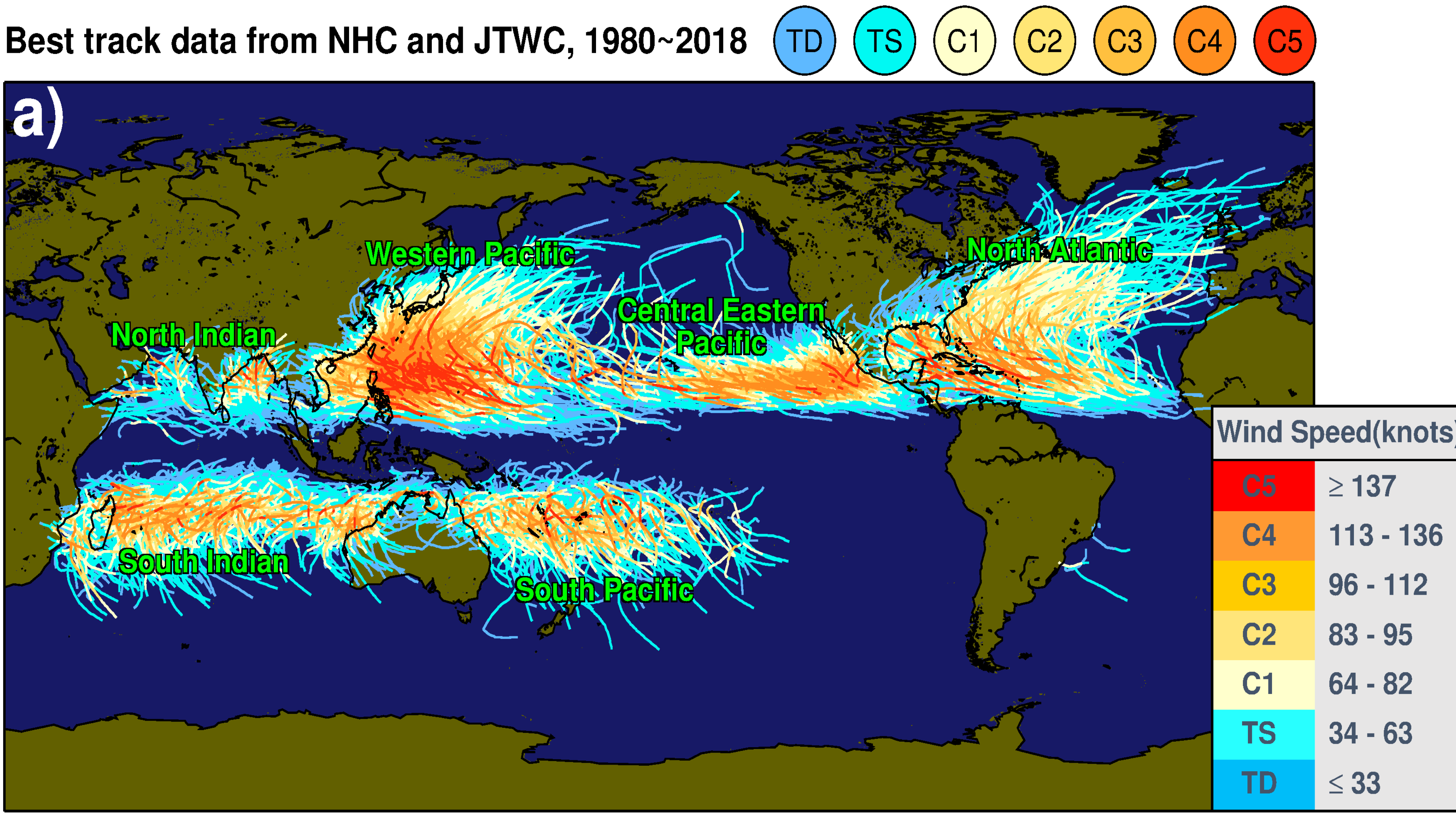


Increase in OCPI but not SSTPI





Best track data from NHC and JTWC, 1980~2018



Lin et al. 2020; Reproduced following NASA Earth Observatory

nature
International journal of science

Jin et al. Nature 2014

Letter

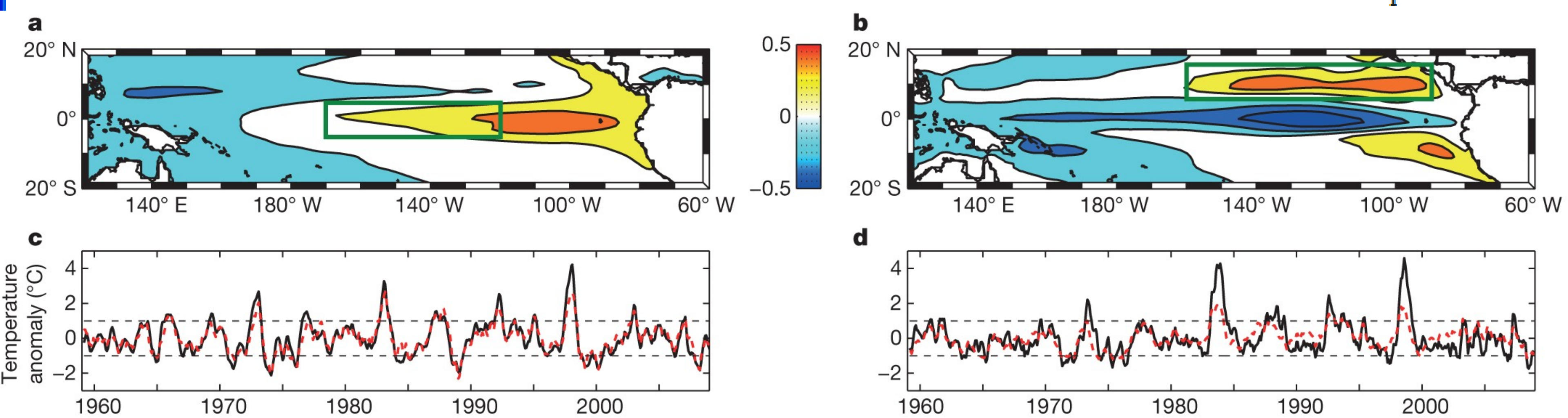
Eastern Pacific tropical cyclones intensified by El Niño delivery of subsurface ocean heat

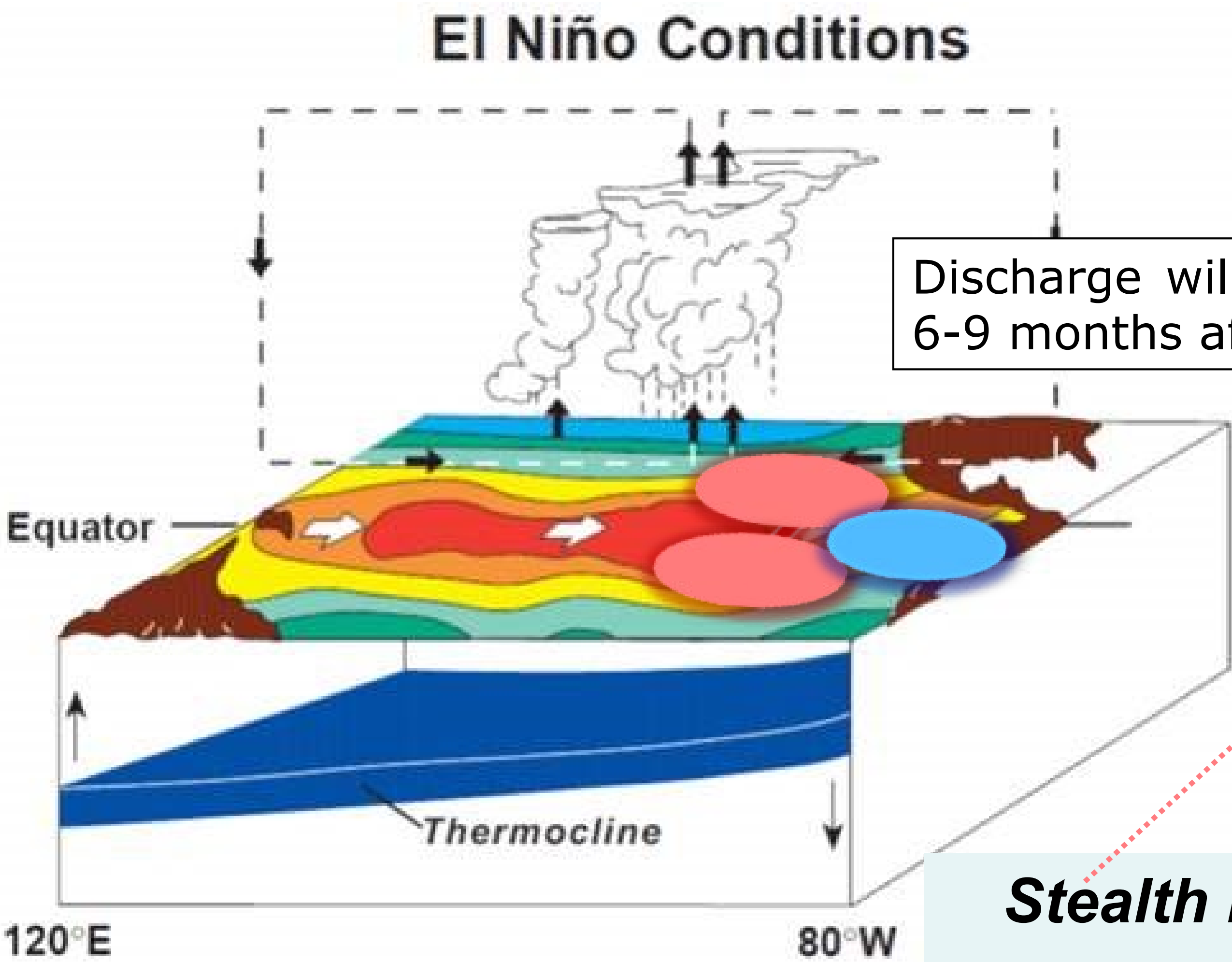
F.-F. Jin, J. Boucharel & I.-I. Lin

Editorial Su

A direct link hurricane

There has bee relating El Ni surface temp equatorial Pa





Discharge will happened about 6-9 months after El Niño peak.

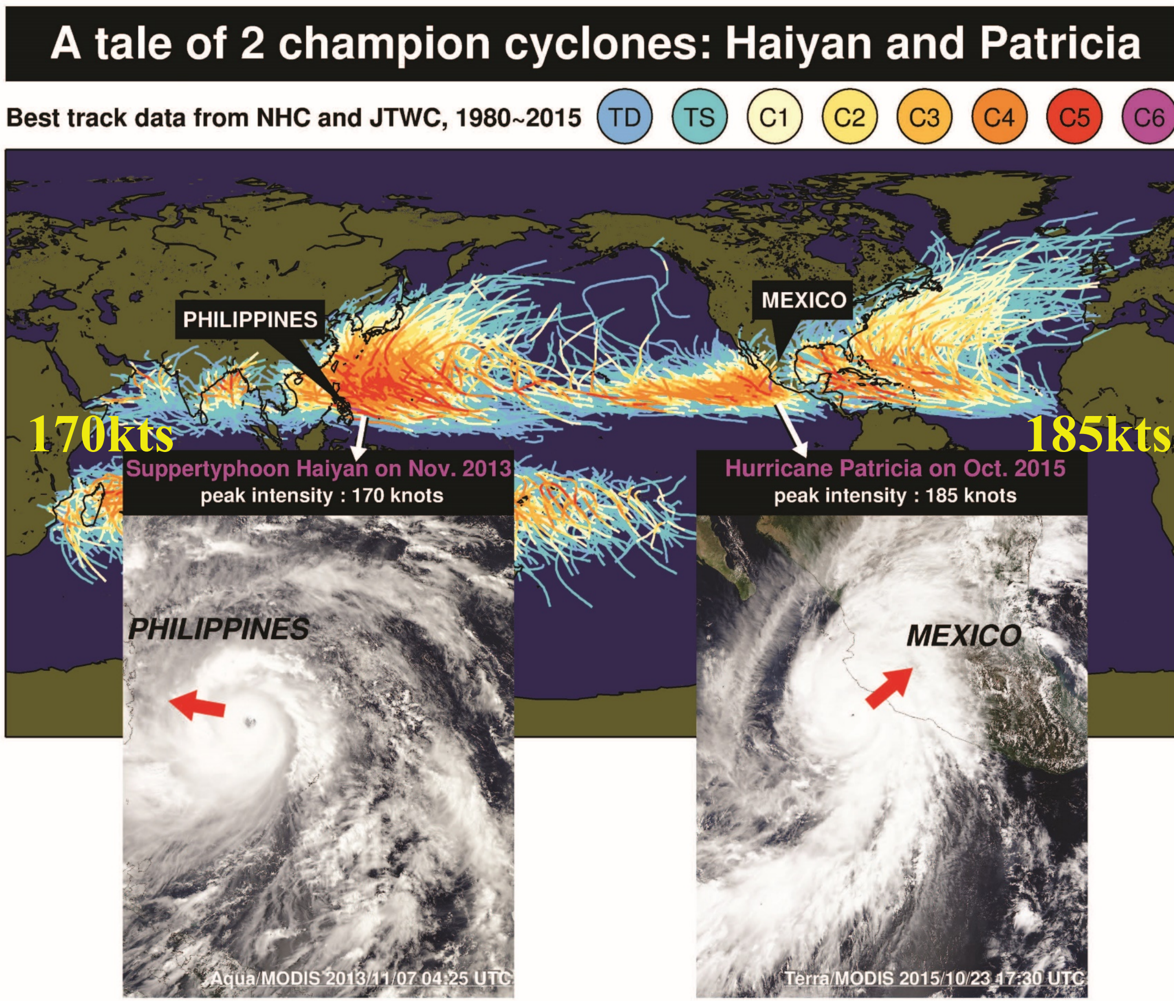
'Secret Santa'

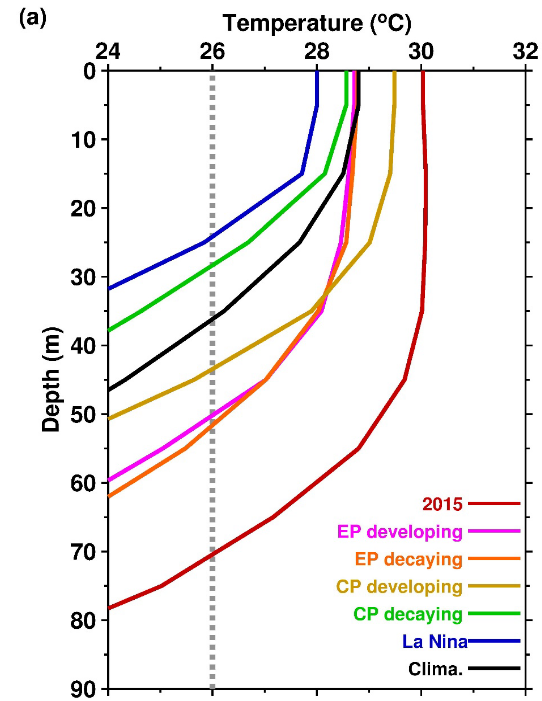
Stealth heat transport via ocean subsurface pathway to fuel CEP Hurricanes (OCPI application)

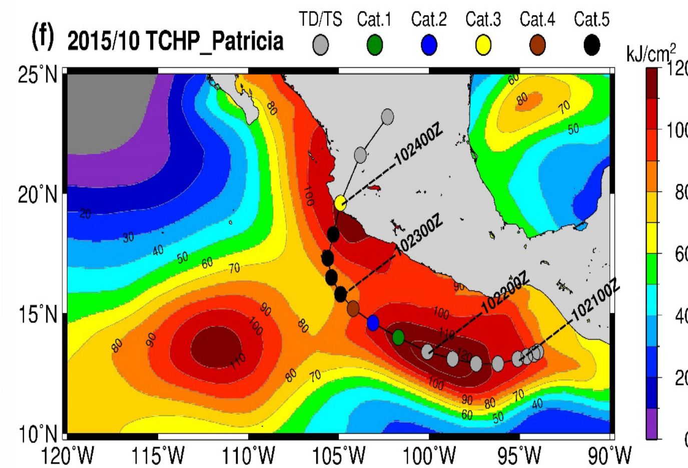
JOURNAL OF GEOPHYSICAL RESEARCH
Oceans
AN AGU JOURNAL
JGR
Volume 122 • Issue 8 • August 2017 • Pages 6067–6964

Huang et a. JGR 2017

Cover, Aug 2017







Warm blob and PMM (Bond et al,2015; Murakami et al. 2017)

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NATURAL HAZARDS News

Probing the Power of Pacific Supertyphoons

Importance of Category '6'

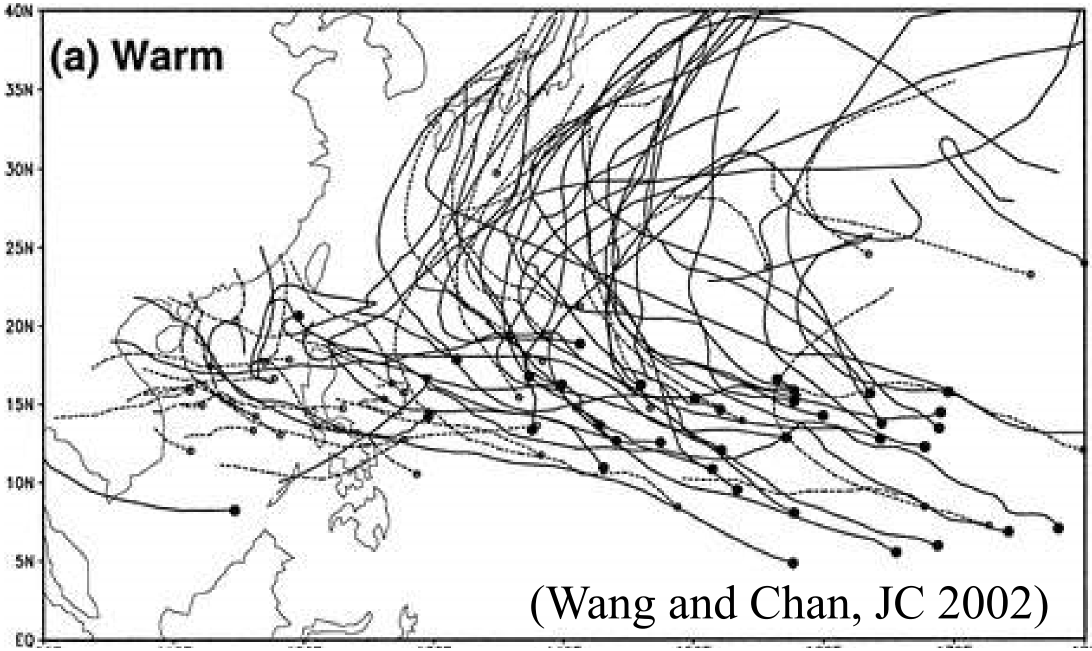
Haiyan (170kts, 2013)

Meranti (165kts, 2016)

Patricia (185kts, 2015)

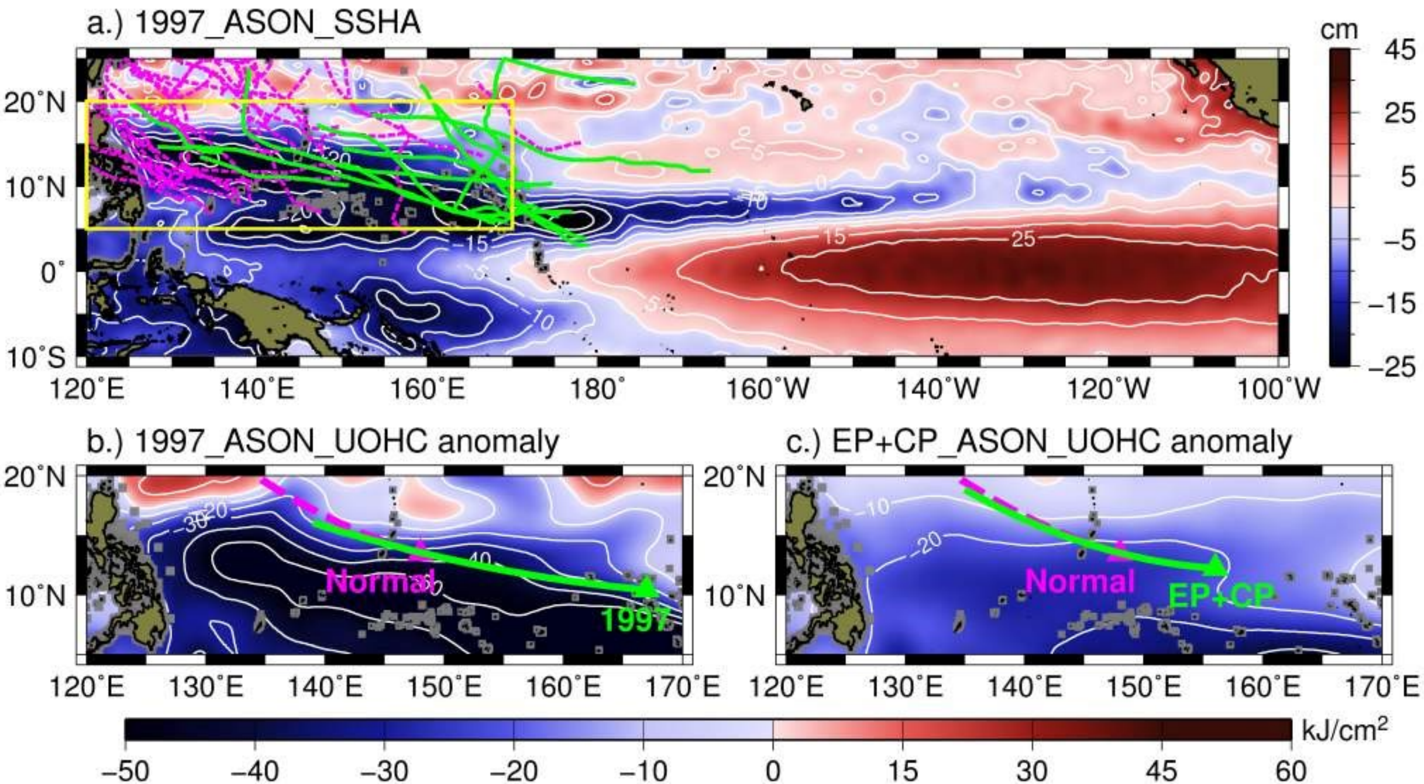
Lin et al. BAMS 2017

El Niño & Typhoons



(Wang and Chan, JC 2002)

But
Megi (2010) &
Haiyan (2013)...

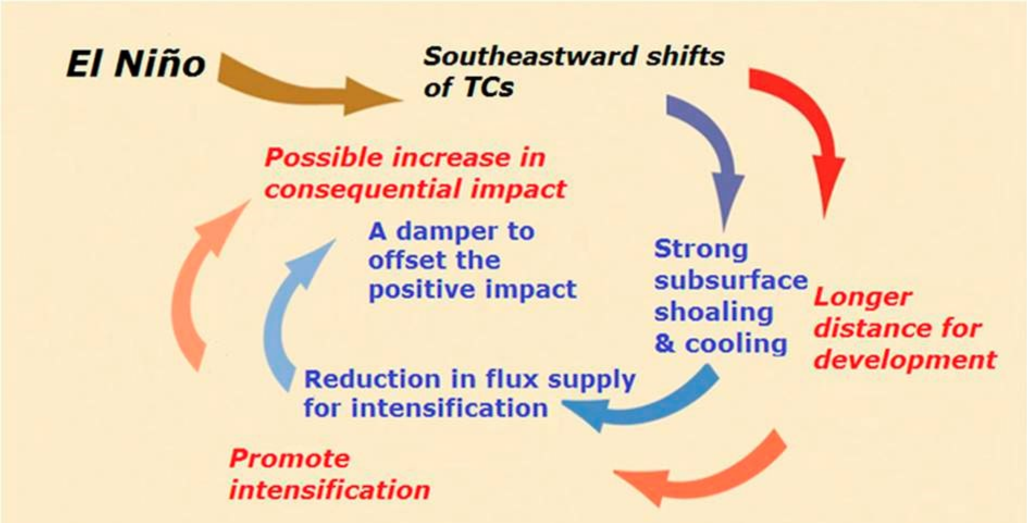


Zheng, Lin, Wang..
et al. Sci. Rep. 2015

(a)	Flux (Wm^{-2})	Distance (km)	Flux × Distance ($10^9 Wm^{-1}$)	Flux × Distance .wrt. normal (%)	Genesis Position
1997 El Niño	500 (46)	3066	1.534 (0.142)	136%	171.01°E 8.94°N
1997 El Niño (if no shoaling)	712 (10)	3066	2.182 (0.029)	194%	171.01 °E 8.94 °N
(b)	Flux (Wm^{-2})	Distance (km)	Flux × Distance ($10^9 Wm^{-1}$)	Flux × Distance .wrt. normal (%)	Genesis Position
8 El Niño composites	597 (16)	2401	1.434 (0.039)	127%	154.68 °E 12.5 °N
8 El Niño composites (if no shoaling)	698 (7)	2401	1.676 (0.017)	149%	154.68 °E 12.5 °N
(c)	Flux (Wm^{-2})	Distance (km)	Flux × Distance ($10^9 Wm^{-1}$)	Flux × Distance .wrt. normal (%)	Genesis Position
Normal condition	583 (16)	1932	1.127 (0.031)	100%	146.98 °E 14.55 °N

Weak Positive After Offset from OHC shoaling

1997 El Niño: 136% .vs. 194%; 8 El Niño composite: 127% .vs.147%



nature COMMUNICATIONS

ARTICLE

Received 8 Jul 2014 | Accepted 10 Apr 2015 | Published 20 May 2015 DOI: 10.1038/ncomms8182 OPEN

Recent decrease in typhoon destructive potential and global warming implications

I-I Lin[1] & Johnny C.L. Chan[2]

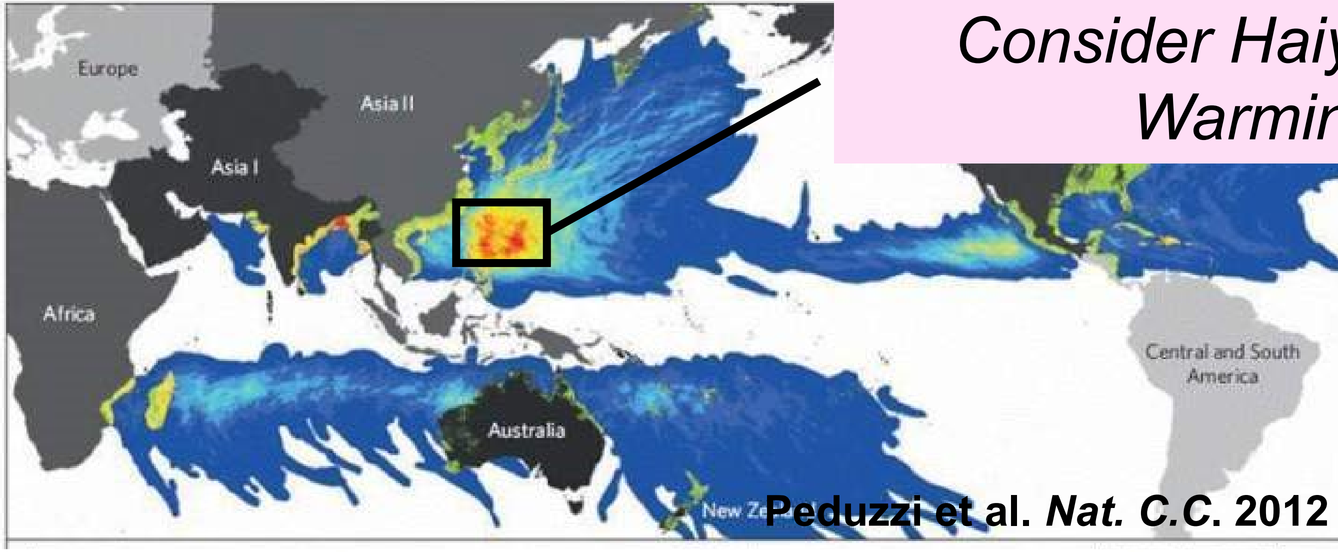
$$\mathrm{PDI} = \int_0^{\tau} V_{\max}^3 \, dt$$

Annual PDI: Sum over all TCs. Thus is a fcn. of

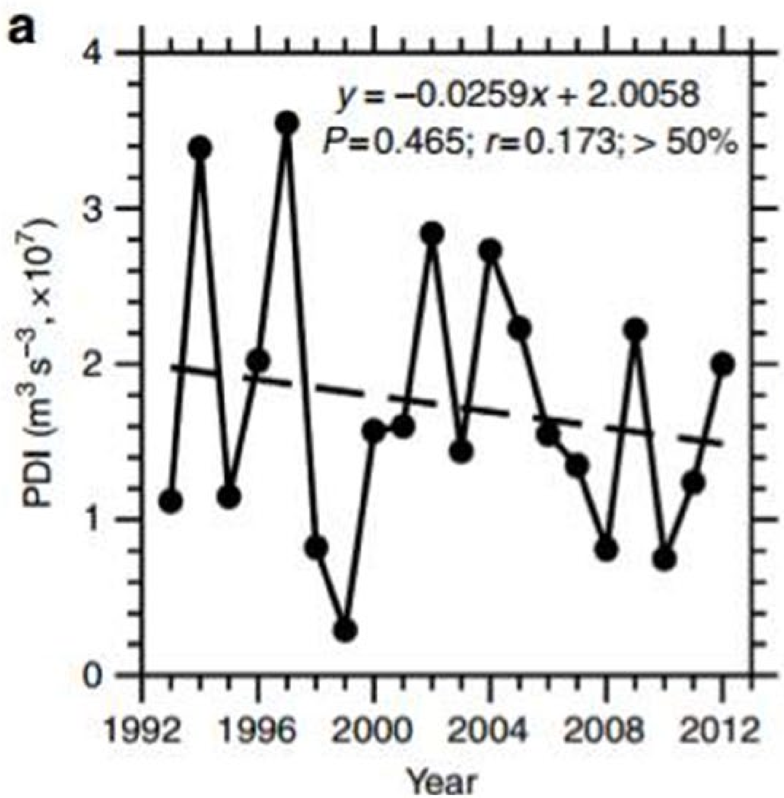
TC occurrence frequency (number), TC duration, TC intensity

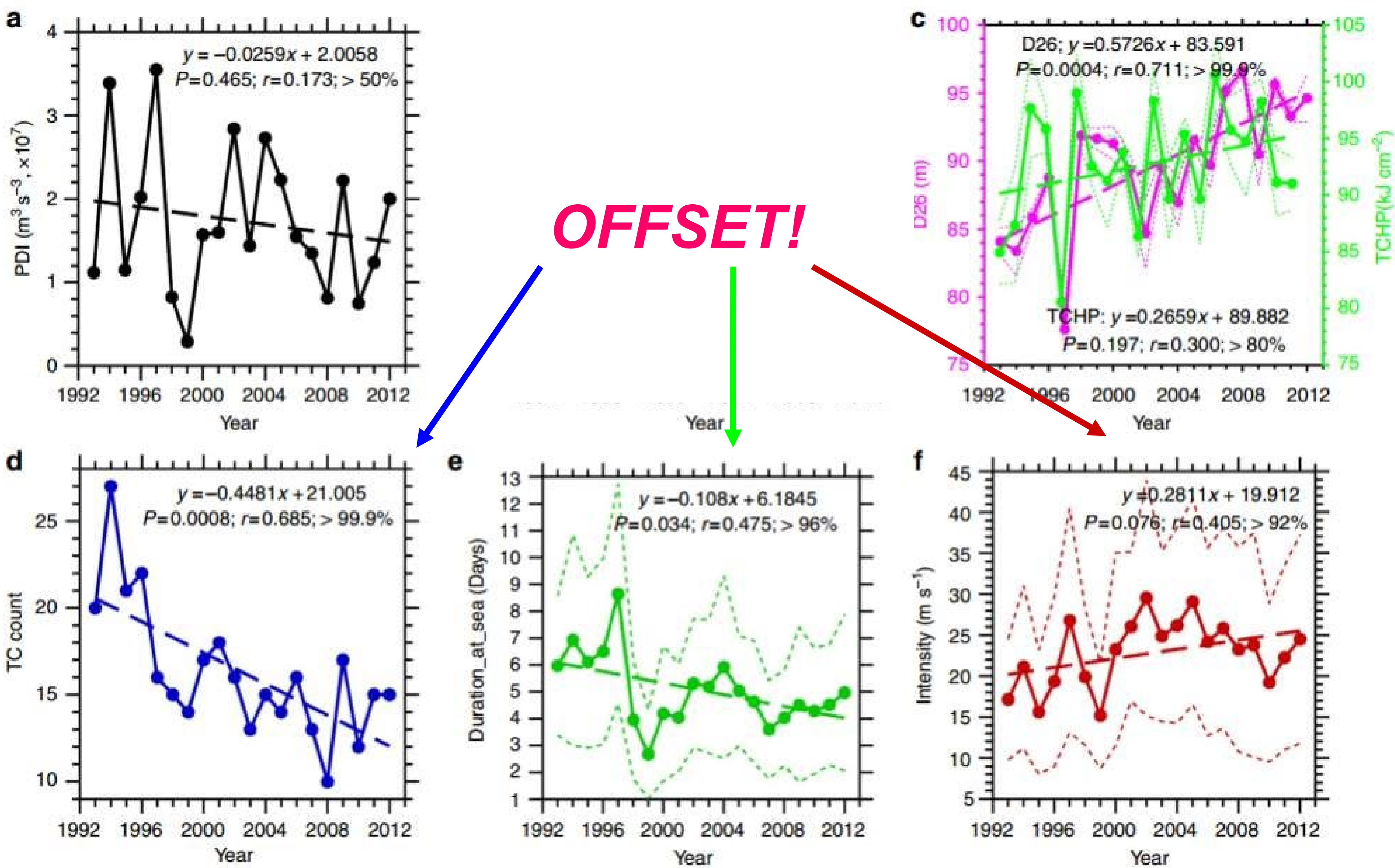
Emanuel 2005

Consider Haiyan, Ocean Warming.....

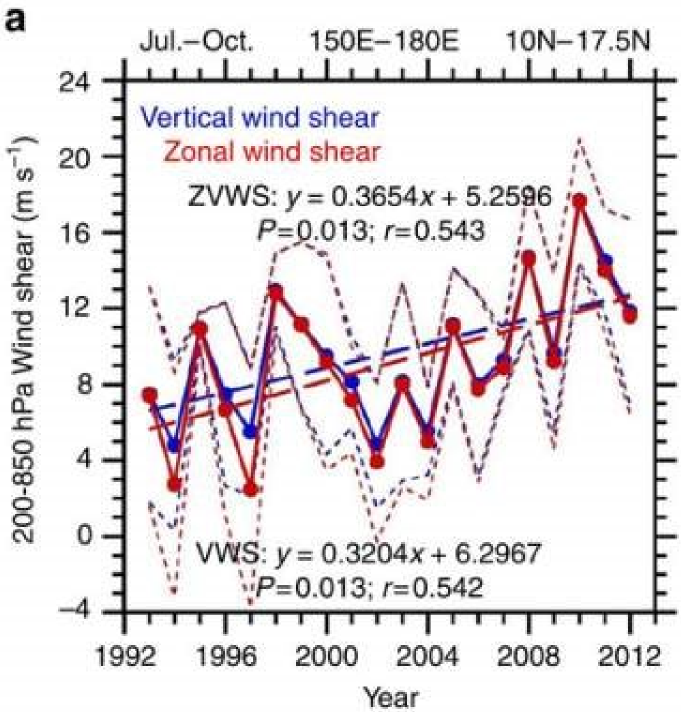


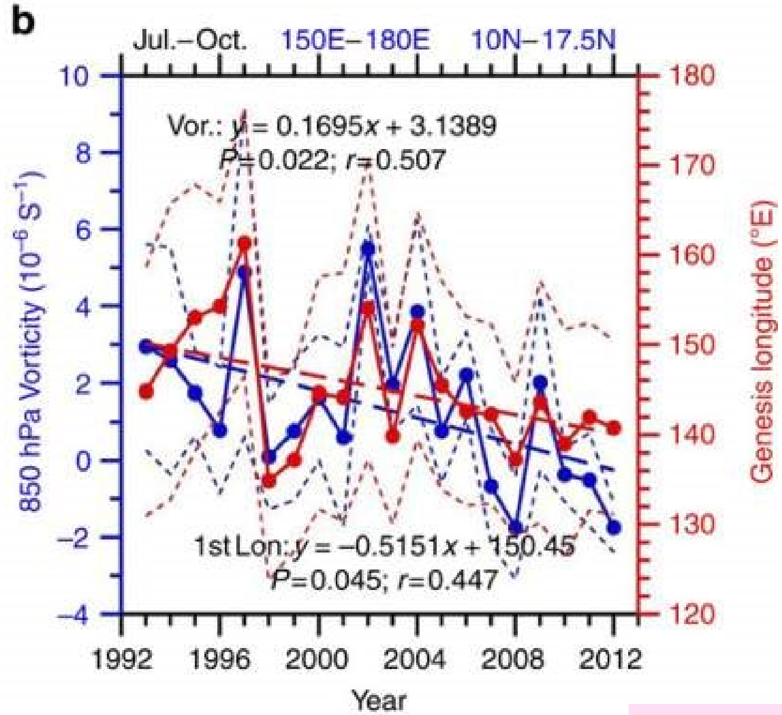
Peduzzi et al. *Nat. C.C.* 2012

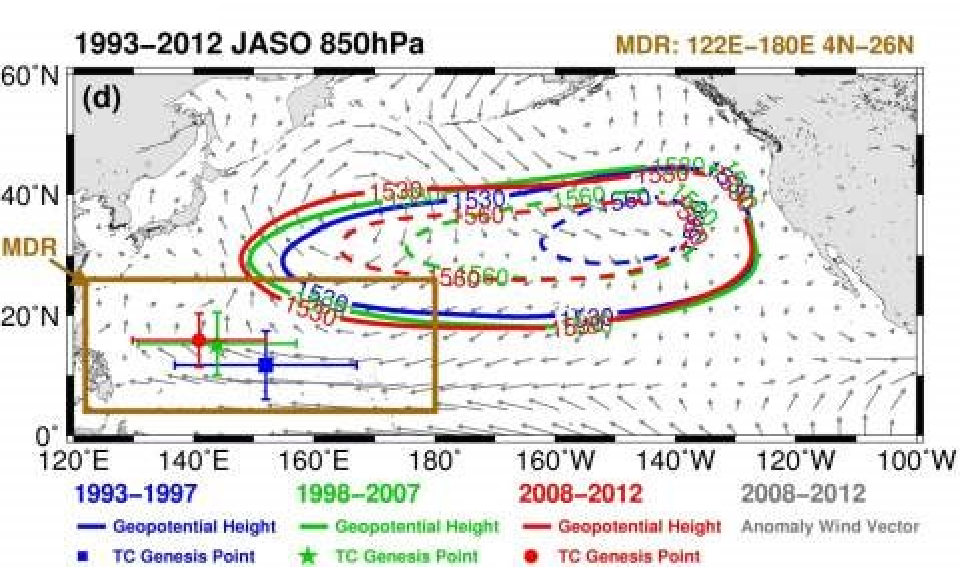




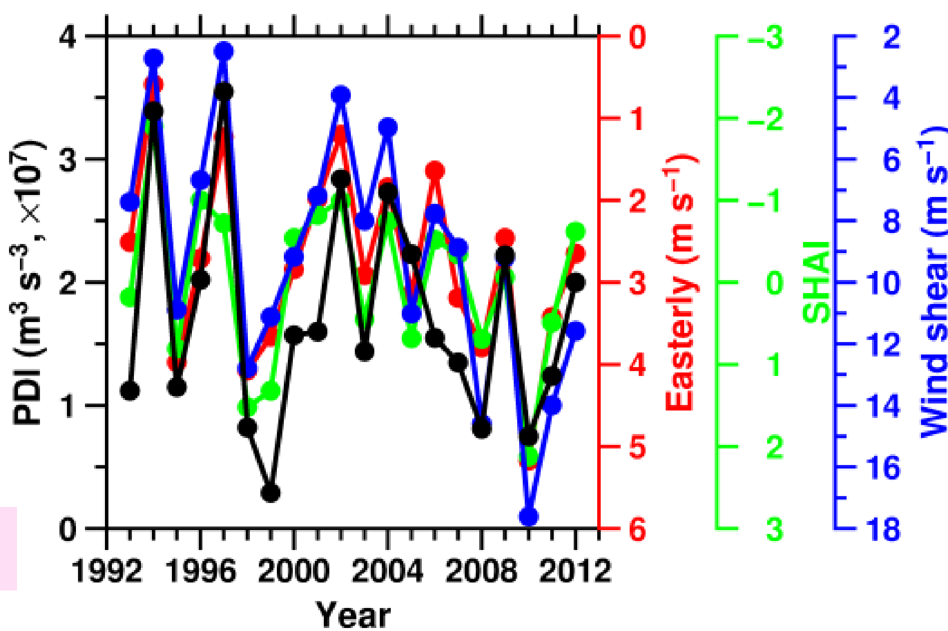
a
y = −0.0259x + 2.0058
P=0.465; r=0.173; > 50%
PDI (m³ s⁻³, ×10⁷)
Year
c
D26; y =0.5726x + 83.591
P=0.0004; r=0.711; > 99.9%
TCHP: y =0.2659x + 89.882
P=0.197; r=0.300; > 80%
D26 (m)
TCHP(kJ cm⁻²)
Year
OFFSET!
d
y =−0.4481x +21.005
P=0.0008; r=0.685; > 99.9%
TC count
Year
e
y =−0.108x +6.1845
P=0.034; r=0.475; > 96%
Duration_at_sea (Days)
Year
f
y =0.2811x + 19.912
P=0.076; r=0.405; > 92%
Intensity (m s⁻¹)
Year







r=-0.83



Sub. High controls both ocean/atm.

Global Warming Condition

Table 3 | PDI in current and global warming scenarios.

Western North Pacific Domain	PDI ($\times 10^7$ $m^3 s^{-3}$; std)	*I*($m\ s^{-1}$; std)	*N*(cases; std)	*D*(days; std)
Current	1.91 (0.38)	28.74 (1.27)	22.28 (4.18)	6.52 (0.71)
Global warming	1.62 (0.44)	30.12 (1.32)	16.55 (3.50)	6.73 (0.99)
Global warming—current	−0.29	+1.38	−5.73	+0.21
% Change with respect to current	−15.2%	+4.8%	−25.7%	+3.2%

PDI, Power Dissipation Index.
Comparison of PDI and the three contributing factors under current and global warming scenarios (late 21st century projection), based on the simulated typhoon data from Zhao and Held[10] and Zhao *et al.*[11] high resolution modelling[58-60].

TC frequency: -25.7% (Neg. contrib.)

Intensity: +4.8% (Pos. contrib.)

PDI: -15.2% in global warming
(less TCs but more intense, a different world)

Lin and Chan Nat. Comm. 2015

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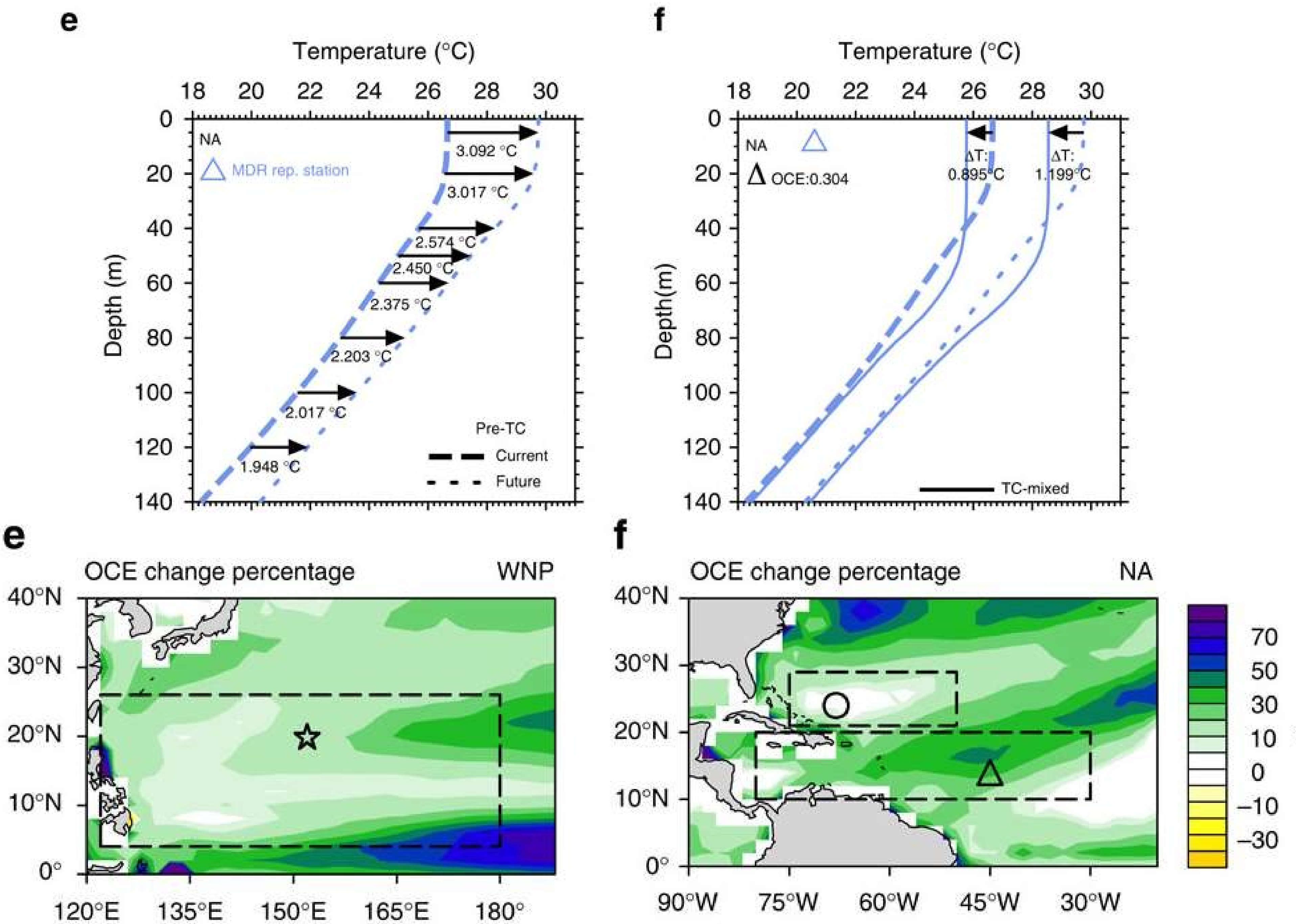
NATURE COMMUNICATIONS | ARTICLE OPEN

Change in ocean subsurface environment to suppress tropical cyclone intensification under global warming

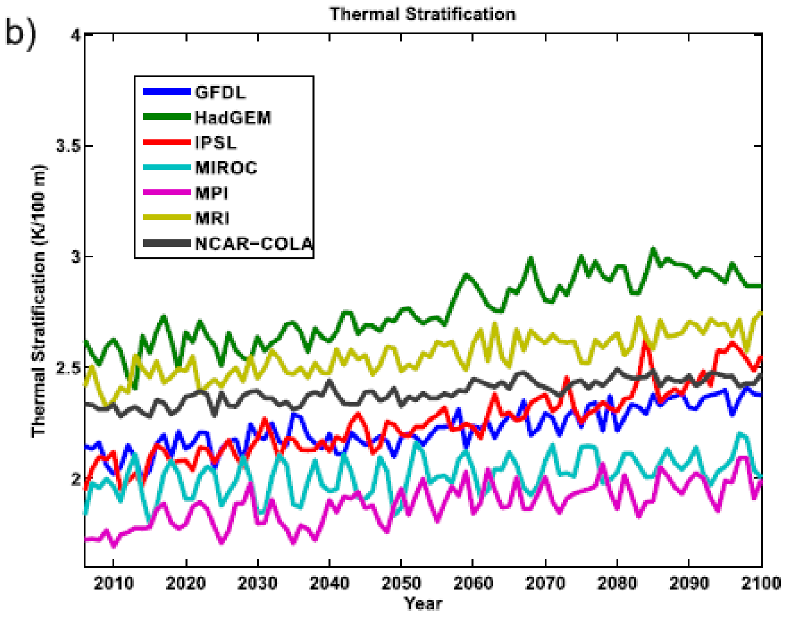
Huang et al. 2015

Ocean community (e.g., Capotondi,et al. JGR 2012): general increase in stratification in global warming

TC Main Development Regions?

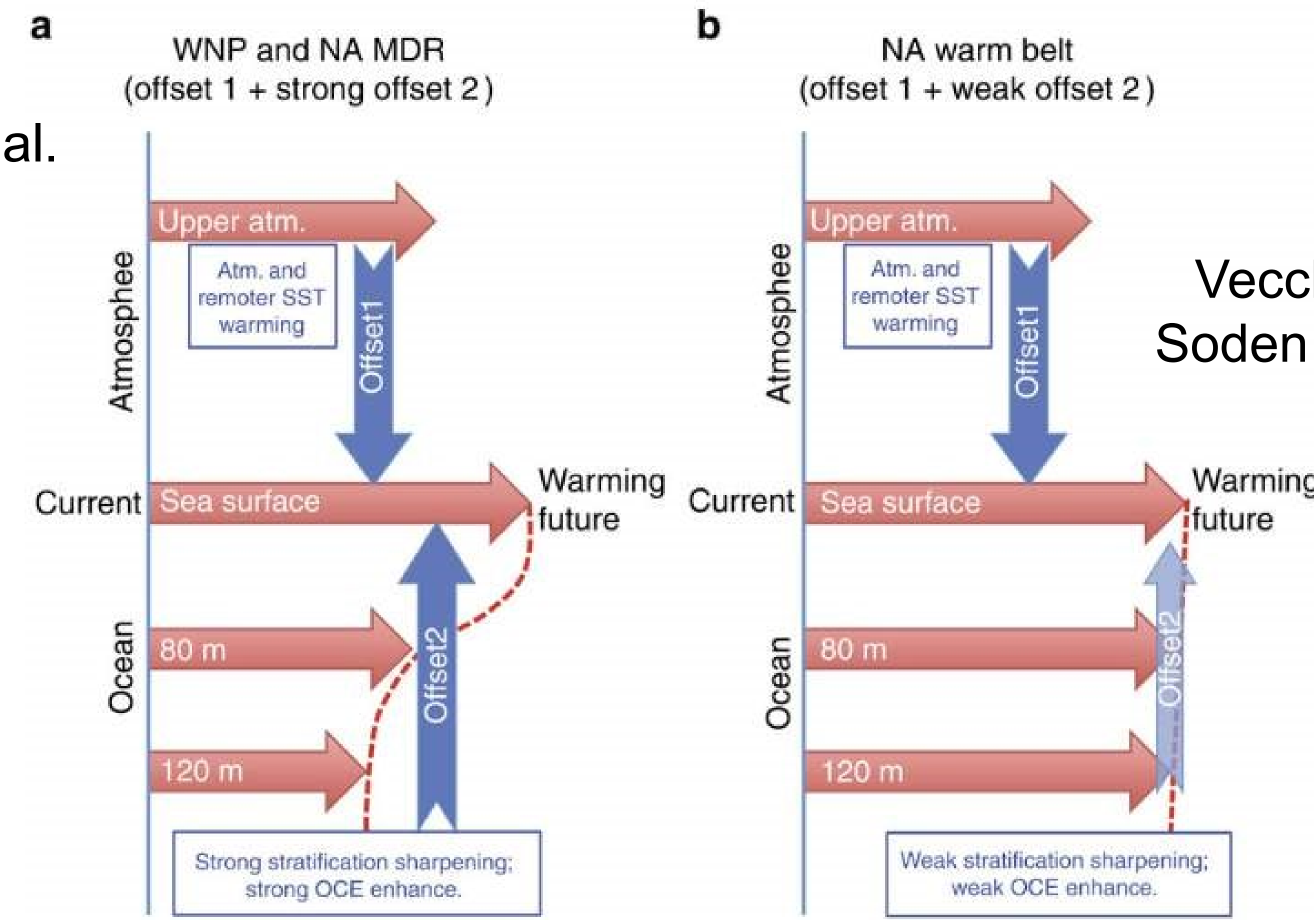

e
Temperature (°C)
18 20 22 24 26 28 30
Depth (m)
0 20 40 60 80 100 120 140
NA
MDR rep. station
3.092 °C
3.017 °C
2.574 °C
2.450 °C
2.375 °C
2.203 °C
2.017 °C
1.948 °C
Pre-TC
Current
Future
f
Temperature (°C)
18 20 22 24 26 28 30
Depth(m)
0 20 40 60 80 100 120 140
NA
Δ OCE:0.304
ΔT: 0.895°C
ΔT: 1.199°C
TC-mixed
e
OCE change percentage
WNP
40°N 30°N 20°N 10°N 0°
120°E 135°E 150°E 165°E 180°
f
OCE change percentage
NA
40°N 30°N 20°N 10°N 0°
90°W 75°W 60°W 45°W 30°W
70 50 30 10 0 −10 −30

ACCESS1-0	HadGEM2-AO (-ES in Emanuel 2015)
ACCESS1-3	IPSL-CM5A-LR
BCC-CSM1-1	IPSL-CM5A-MR
CCSM4	IPSL-CM5B-LR
CMCC-CESM	MIROC-ESM-CHEM
CMCC-CM	MIROC-ESM
CMCC-CMS	MIROC5
CNRM-CM5	MPI-ESM-LR
CSIRO-Mk3-6-0	MPI-ESM-MR
FGOALS-g2	MRI-CGCM3
GFDL-CM3	NorESM1-M



Emanuel JC 2015

Huang et al. 2015

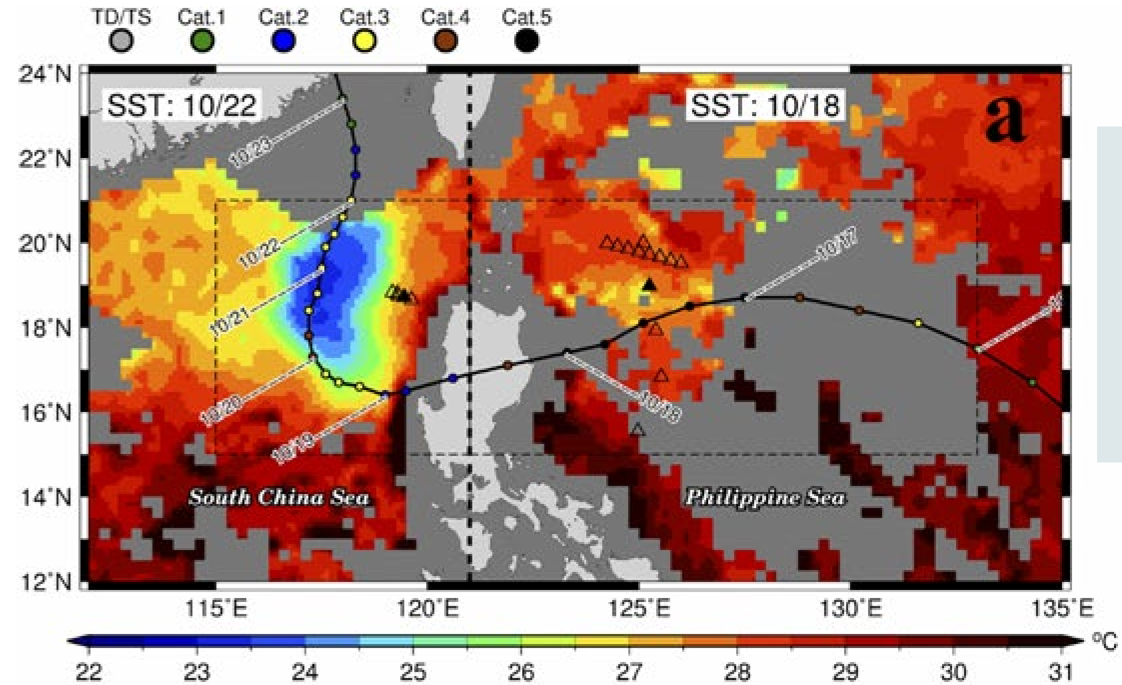


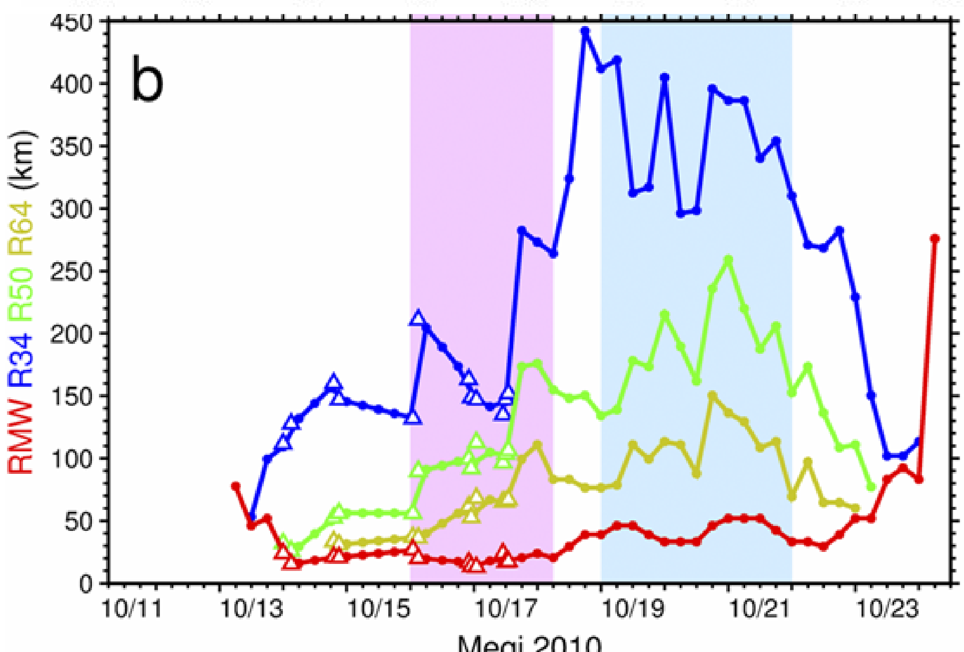
Vecchi & Soden 2007

Emanuel 2015

	GFDL	HadGEM	IPSL	MIROC	MPI	MRI	NCAR–COLA	mean
Overall frequency	−2 (0.19)	0 (0.60)	0 (0.96)	−2 (0.03)	1 (0.82)	−2 (0.79)	0	−1 (0.14)
Frequency of hurricanes	−2 (0.31)	0 (0.91)	−4 (0.21)	−5	1 (0.80)	−1 (0.56)	0 (0.67)	−2 (0.02)
Frequency of category 1	5 (0.65)	2 (0.55)	7 (0.73)	6 (0.42)	9 (0.35)	9 (0.41)	1 (0.87)	3 (0.02)
Frequency of category 2	46 (0.07)	27 (0.06)	94 (0.25)	3 (0.83)	−33 (0.30)	−114	−1 (0.94)	34
Frequency of category 3	20 (0.42)	−1 (0.92)	14 (0.67)	13 (0.43)	106 (0.36)	14 (0.47)	9 (0.59)	11 (0.19)
Frequency of category 4	7 (0.56)	17 (0.04)	−3 (0.84)	−17 (0.13)	21 (0.39)	−5 (0.74)	10 (0.12)	4 (0.40)
Frequency of category 5	−19	−16	−24	−22	−8 (0.13)	−15	−6 (0.05)	−15
Power dissipation	−22	−10	−13	−14	−14 (0.07)	−24	−2 (0.05)	−13

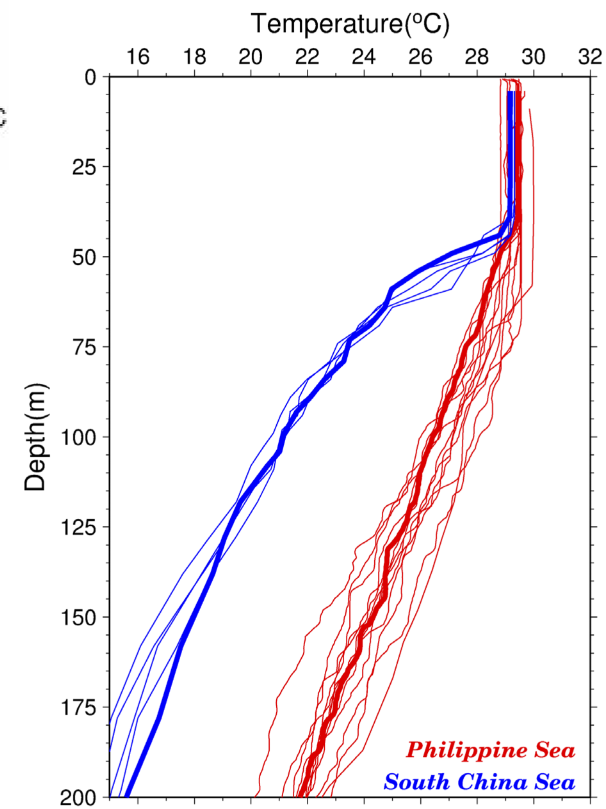
Pun et al. MWR 2018





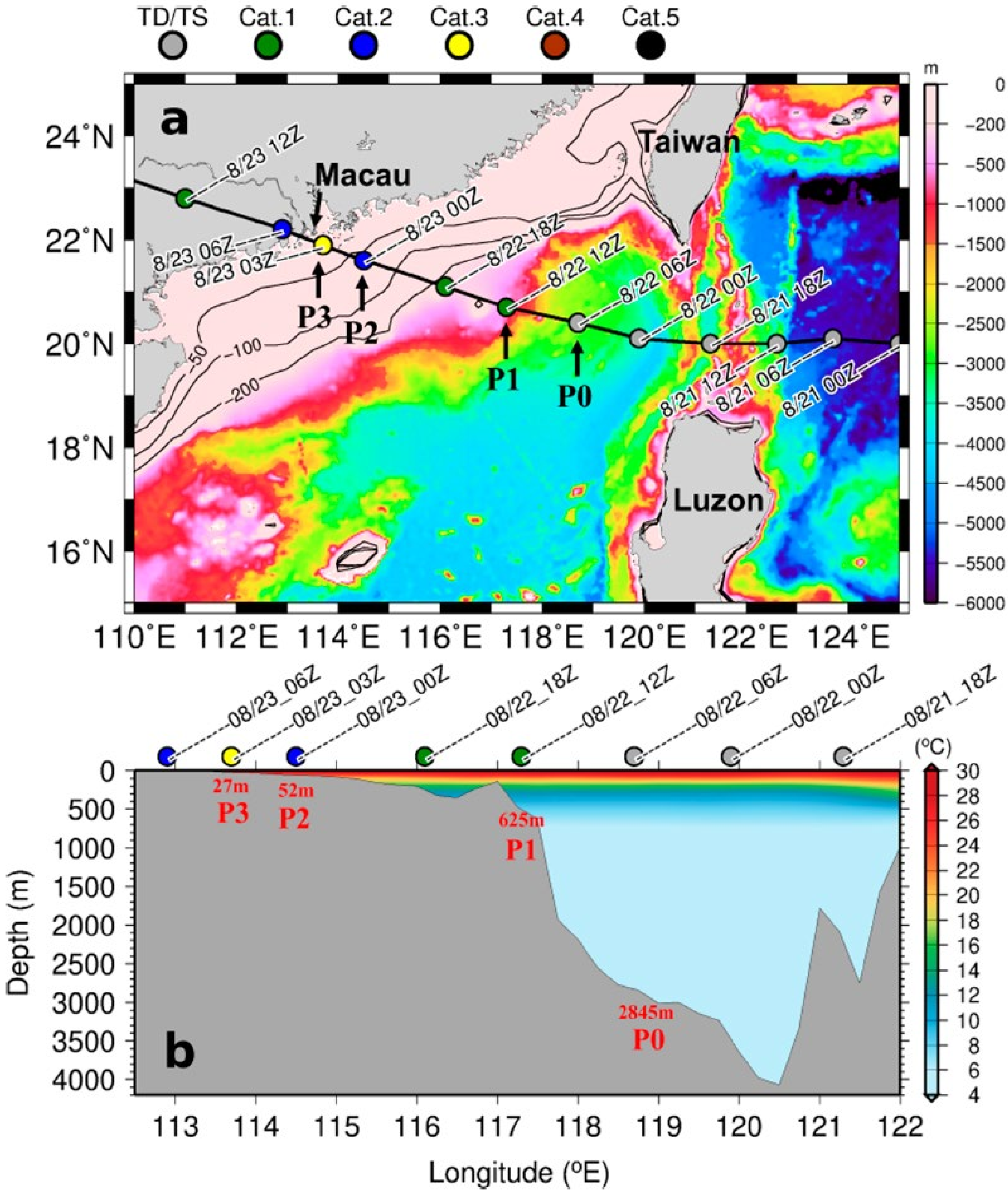
TC size matters

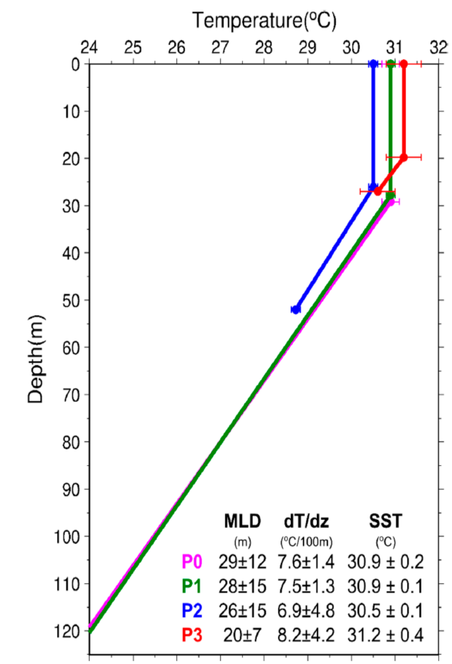
1.9 to 4 ∘C cooling, if without size effect , 52% less cooling



Pun et al. Sustainability 2019

Rapid Intensification of Hato (2017) over shallow water





nature > letters > article

a natureresearch

nature

Letter | Published: 06 June 2018

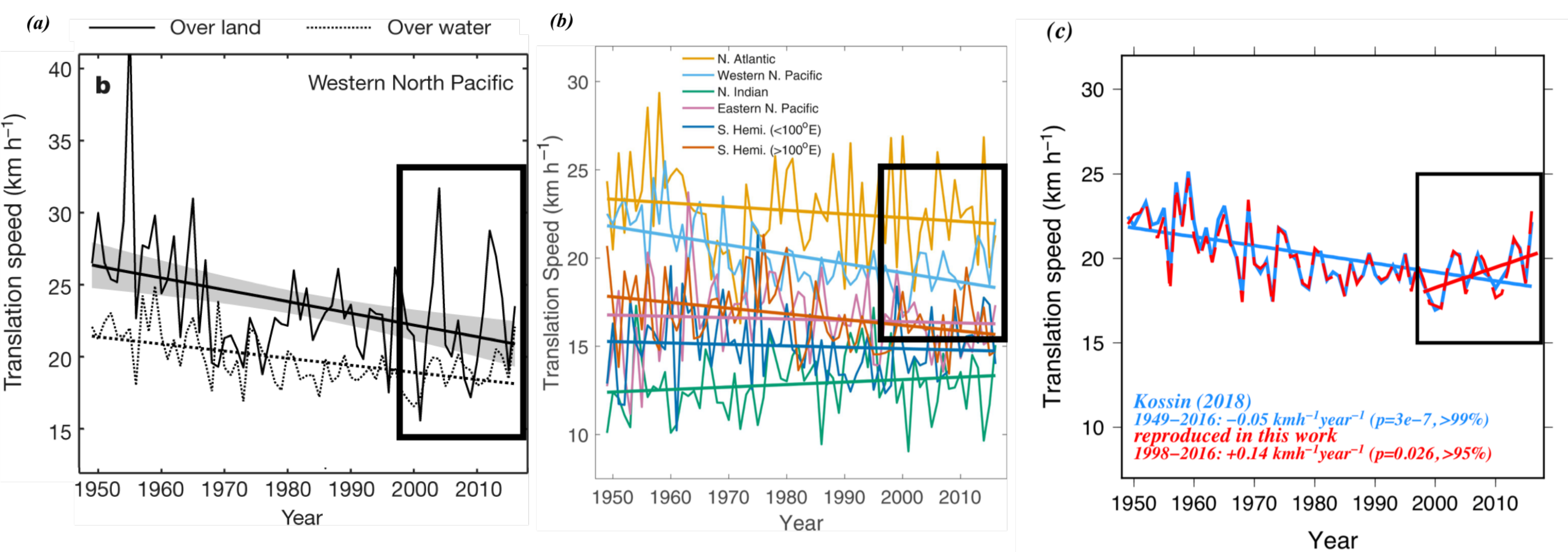
A global slowdown of tropical-cyclone translation speed

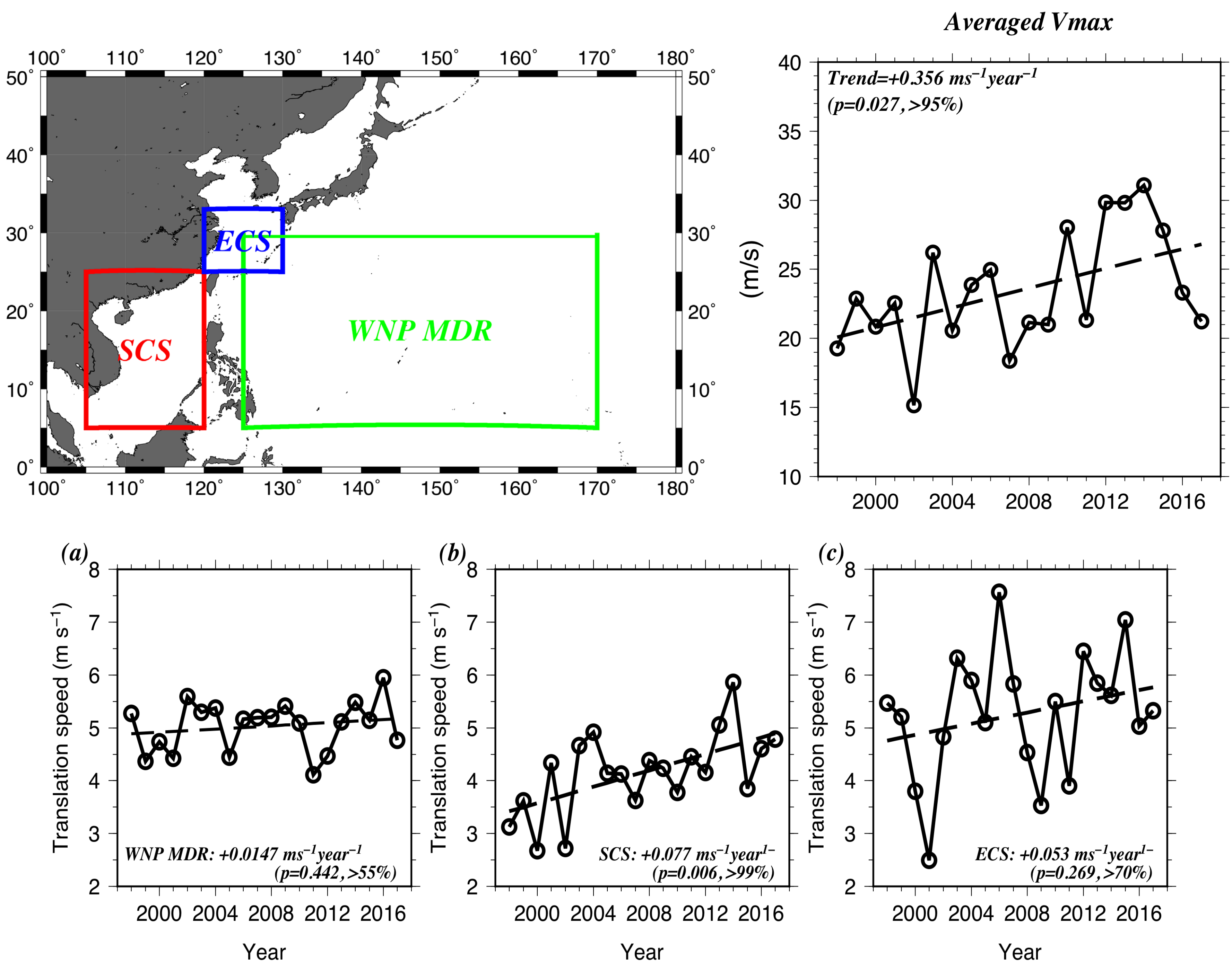
James P. Kossin

Nature **558**, 104–107(2018) | Cite this article

Chang et al. Sustainability 2020

TC Translation Speed & Intensity over the SCS





Averaged Vmax
Trend=+0.356 ms⁻¹year⁻¹
(p=0.027, >95%)
(m/s)
ECS
SCS
WNP MDR
(a)
(b)
(c)
Translation speed (m s⁻¹)
WNP MDR: +0.0147 ms⁻¹year⁻¹
(p=0.442, >55%)
SCS: +0.077 ms⁻¹year¹⁻
(p=0.006, >99%)
ECS: +0.053 ms⁻¹year¹⁻
(p=0.269, >70%)
Year

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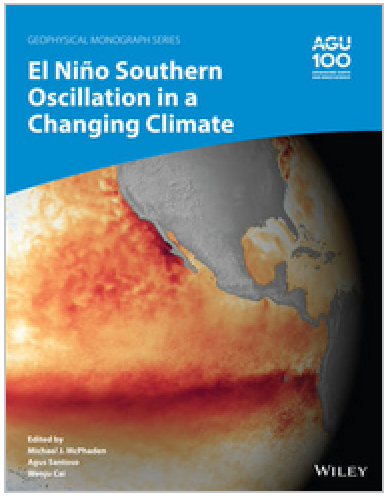

El Niño Southern Oscillation in a Changing Climate

Michael J. McPhaden (Editor), Agus Santoso (Editor), Wenju Cai (Editor)

ISBN: 978-1-119-54812-6 | August 2020 | American Geophysical Union | 528 Pages

PRINT
Starting at just $249.95

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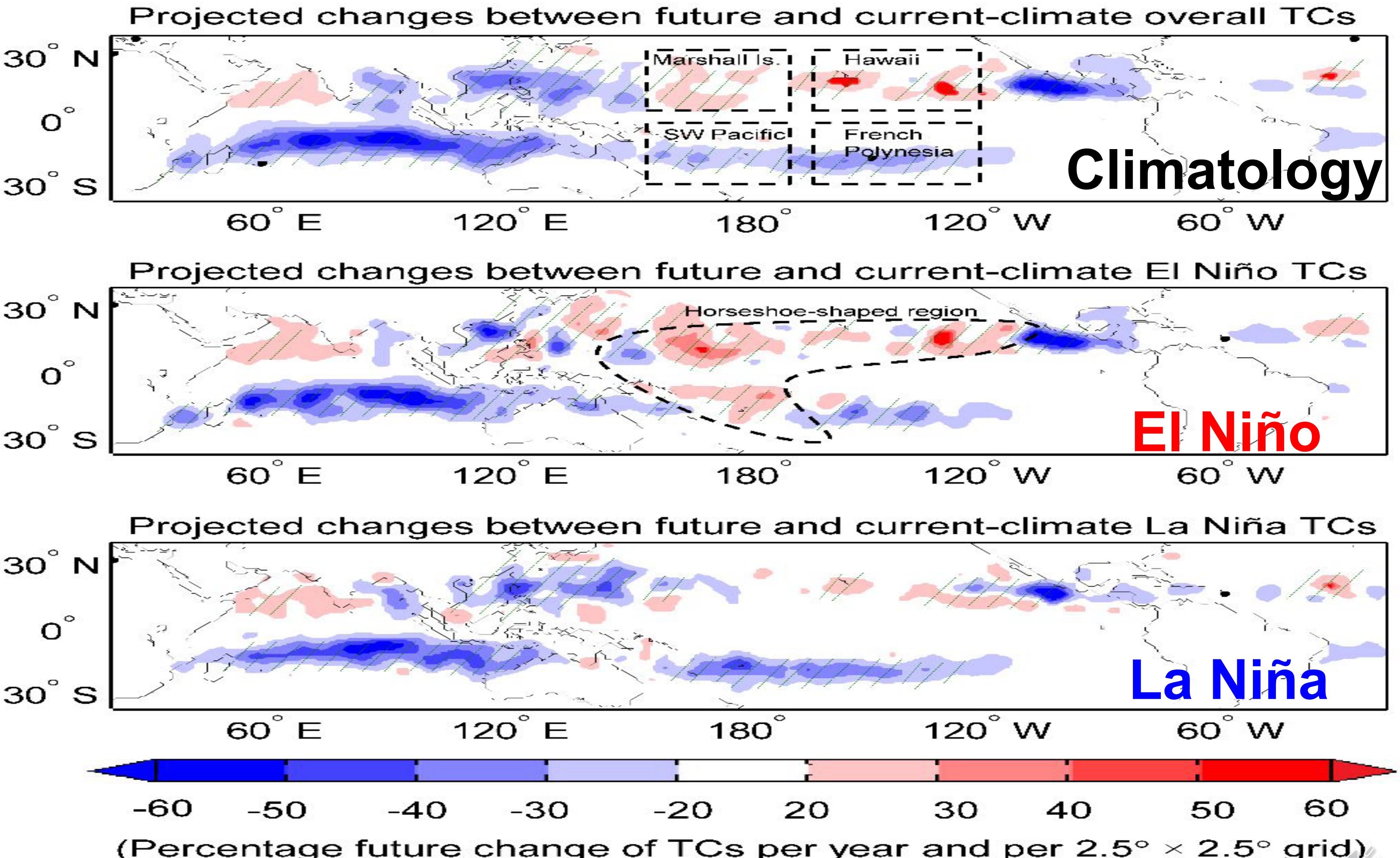
AGU Centennial Monograph, Aug. 2020

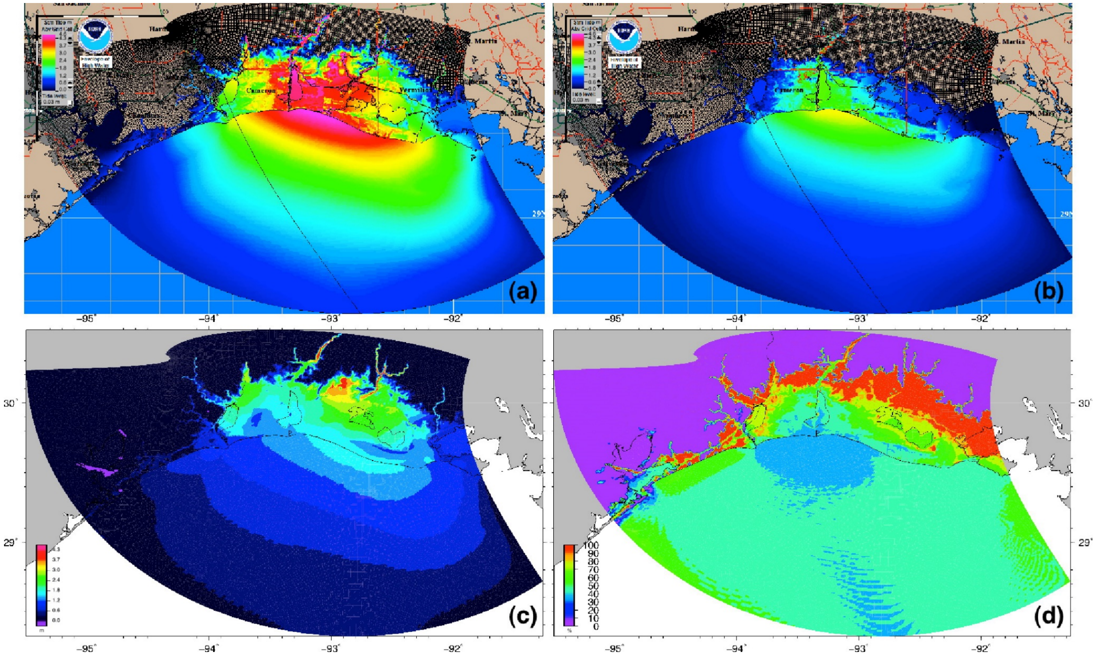
Chap. 17 ENSO and Tropical Cyclones

I. Lin, S.J. Camargo, C.M. Patricola, J. Boucharel, S. Chand, P. Klotzbach, J.C L Chan, B. Wang, P. Chang, T. Li, & F.F. Jin

Chand et al. 2017; Bell et al. 2020

Global Warming, TC, and ENSO

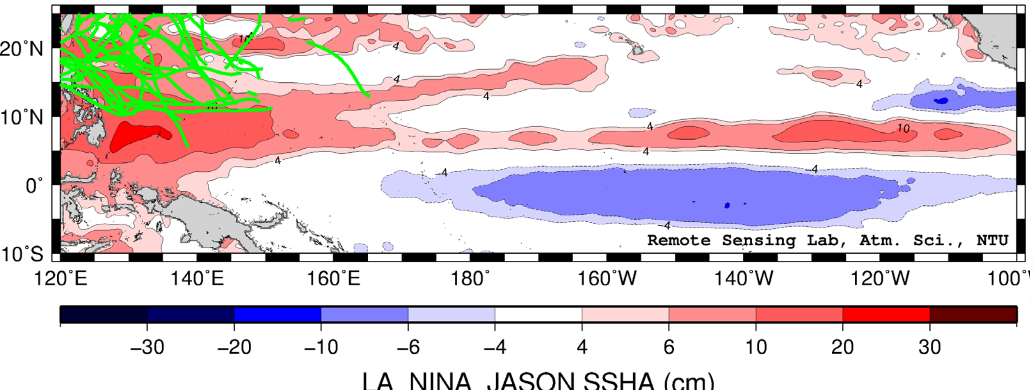


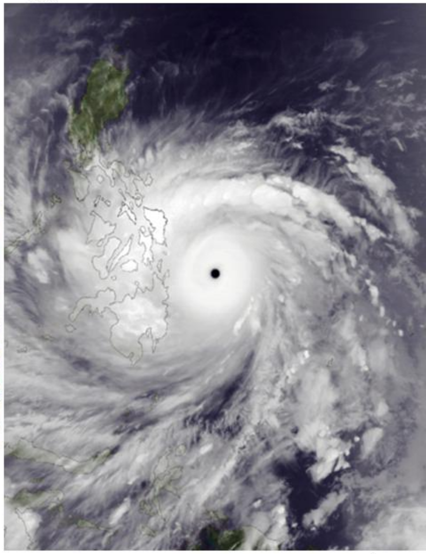


Hurricane Rita (2005)

Lin et al. Nat. Haz. 2013

Global Warming, Sea Level Rise, Extreme La Nina (Chap. 13), &Surge





Death: 6300; Injured: 28689;

Damage : US $ 2,051,710,653 (2 billion)

http://en.wikipedia.org/wiki/Typhoon_Haiyan

TC Haiyan, Lin et al. GRL 2014

Summary

1. **Weather: Rapid Intensification (RI), Ocean Eddy, TC Translation Speed (Uh), TC Size, Shallow Water RI**

2. **ITOP & Ocean Coupling Potential Intensity**

3. **Climate: Cat. 6, Haiyan/Hiatus, Patricia/2015 El Niño, ElNiño's stealth heat supply, South China Sea Uh/intensity trend**

4. **Global Warming**
   PDI reduction, Increase in subsurface stratification,
   Sea level rise and surge, Global Warming-Future ENSO-TC

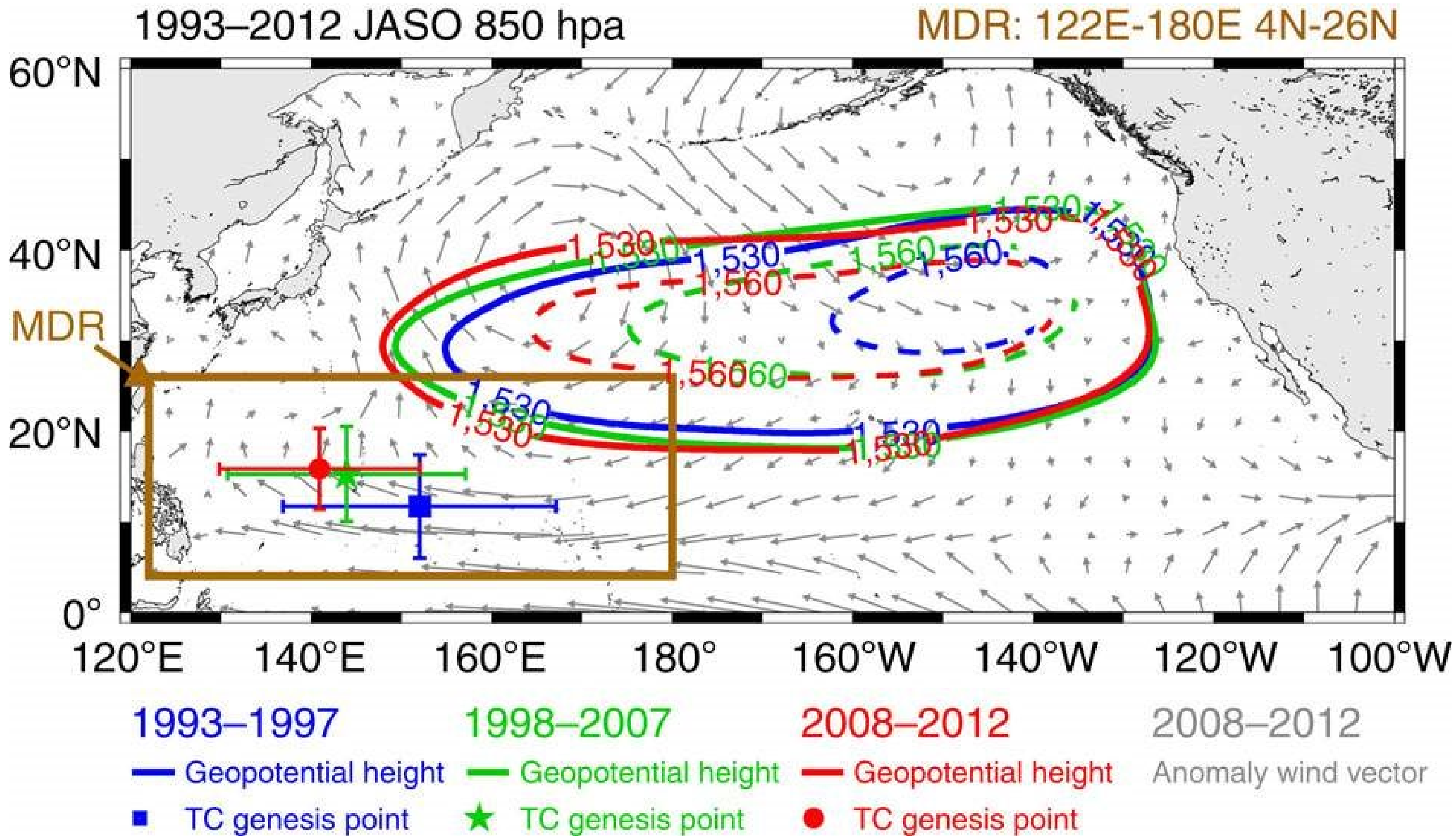
5. **Offset, Competition (Atm./Ocean), & Gaia**
   Inter-annual, Multi-decadal, Centennial/Global Warming Scales

Negative process exist to offset positive processs to prevent TCs from developing towards only 1 direction


QuickTime?and a
decompressor
are needed to see this picture.
Who can understand how He spreads
out the clouds....? Job 36(29)
Brightness Temp
NPP
Precip
Irradiance
Ozone
3-D Clouds
謙卑人必承受地土，以豐盛的平安為樂
詩篇 37(11)
Courtesey: NASA, SC Tsai

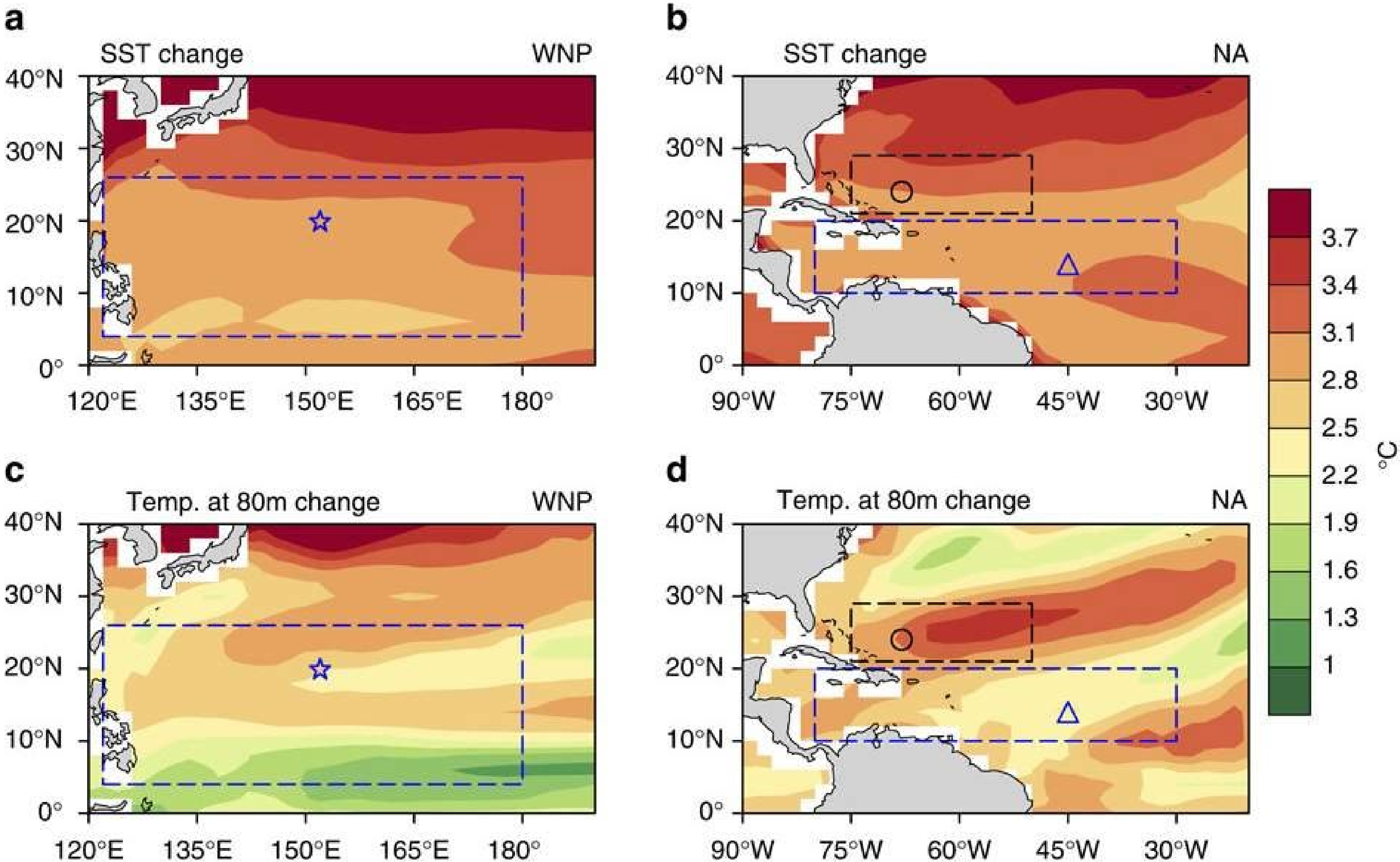
Positive process: subtropical high strengthening contributes to ocean subsurface warming, increase intensity

Negative process: sub-high strengthen also causes increase in shear and decrease in vorticity (worsen atmospheric dynamic factors)!

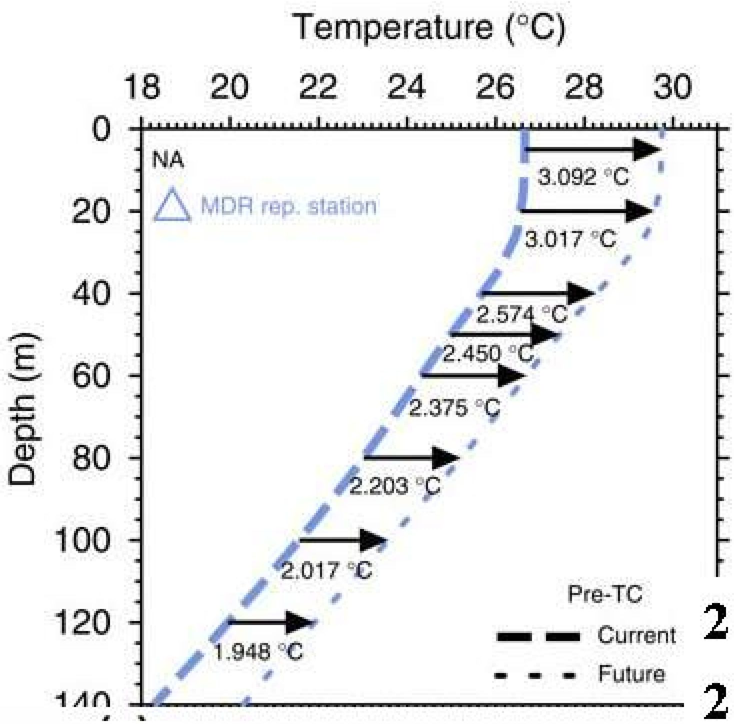


Lin and Chan, Nature Comm. (2015)

Future - Current

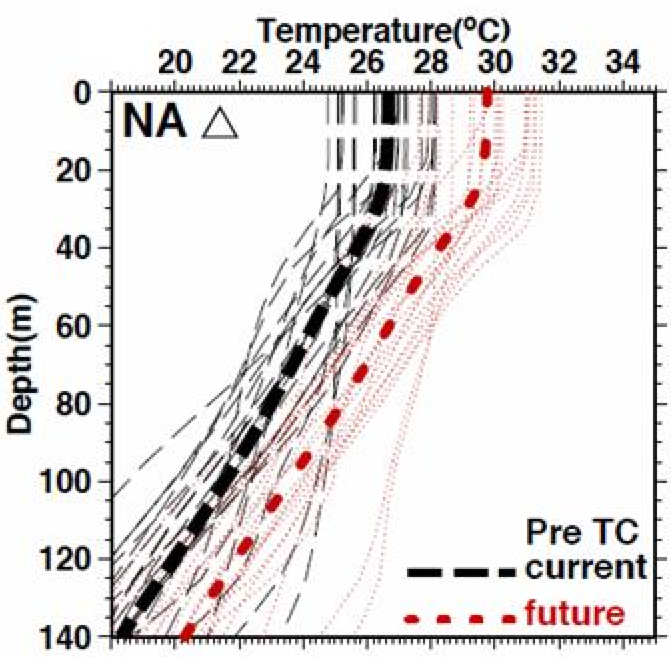


In global warming, the increasing downward heat flux from CO2 heat surface (top maps) first and then subsurface (bottom), ocean subsurface thus warms less than SST and profile gradient sharpens.



2006–2014

2092-2100

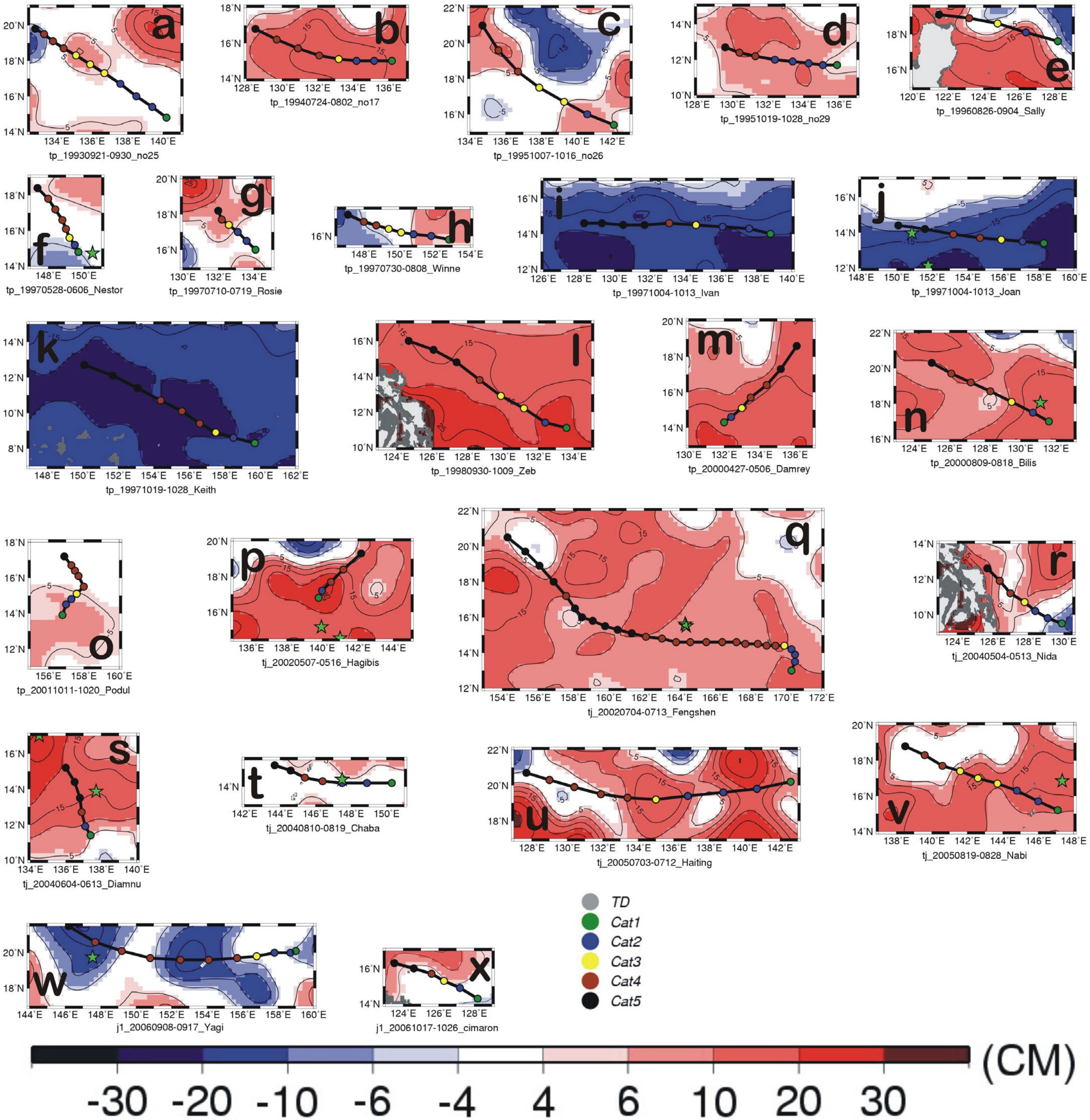


Multi-Model Ensemble (RCP 8.5 of 22 models) over NA MDR shows increase in stratification (slope sharpening) under global warming, because SST warms faster than subsurface ocean.

21/22 ensemble members shows sharpening in representative station

Consistent results is found in WNP MDR

10-20° N



a
tp_19930921-0930_no25
b
tp_19940724-0802_no17
c
tp_19951007-1016_no26
d
tp_19951019-1028_no29
e
tp_19960826-0904_Sally
f
tp_19970528-0606_Nestor
g
tp_19970710-0719_Rosie
h
tp_19970730-0808_Winne
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j
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l
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m
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o
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tj_20020704-0713_Fengshen
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x
j1_20061017-1026_cimaron
TD
Cat1
Cat2
Cat3
Cat4
Cat5
-30 -20 -10 -6 -4 4 6 10 20 30
(CM)

30 Category-5 supertyphoons May-October, 1993-2005