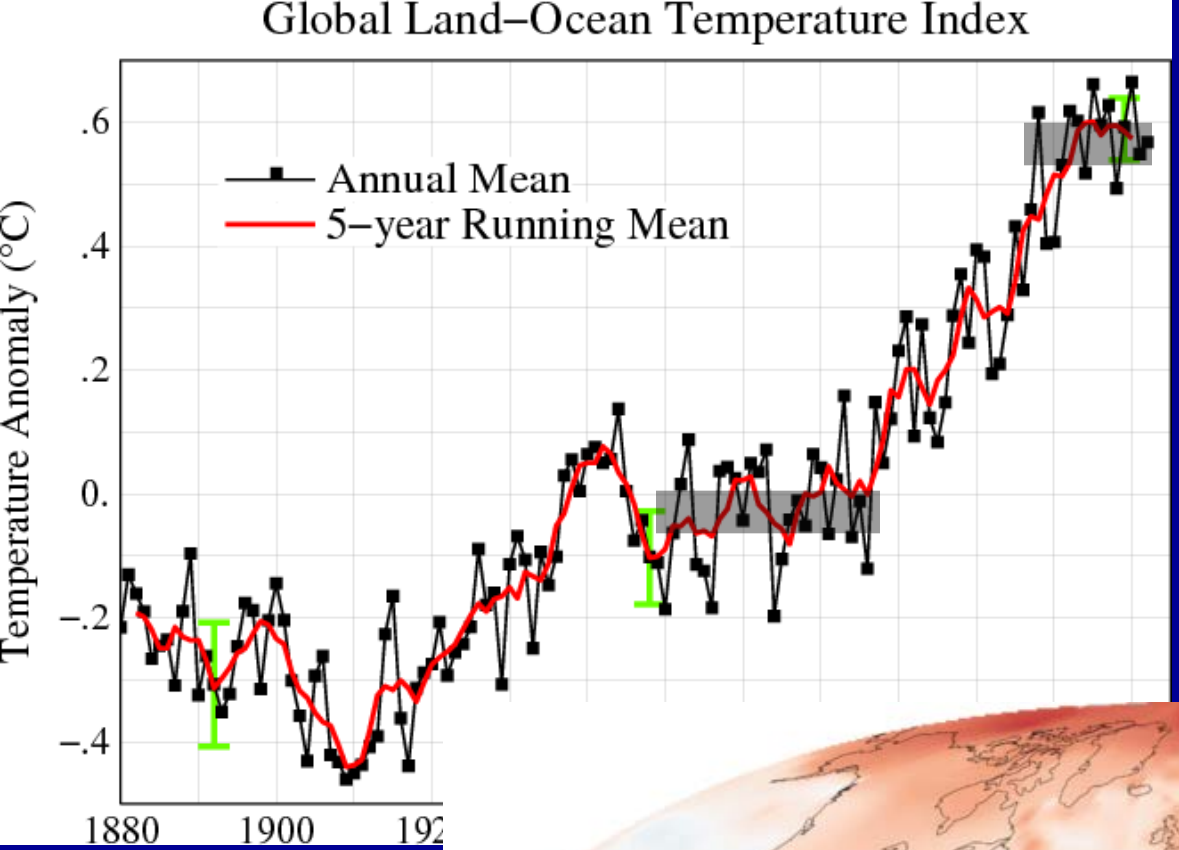
Climate Change and Tropical Cyclones: Past and Future

Alexey Fedorov

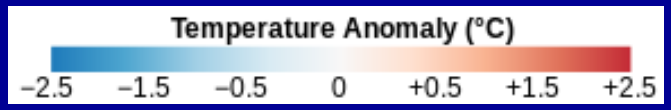
Yale University

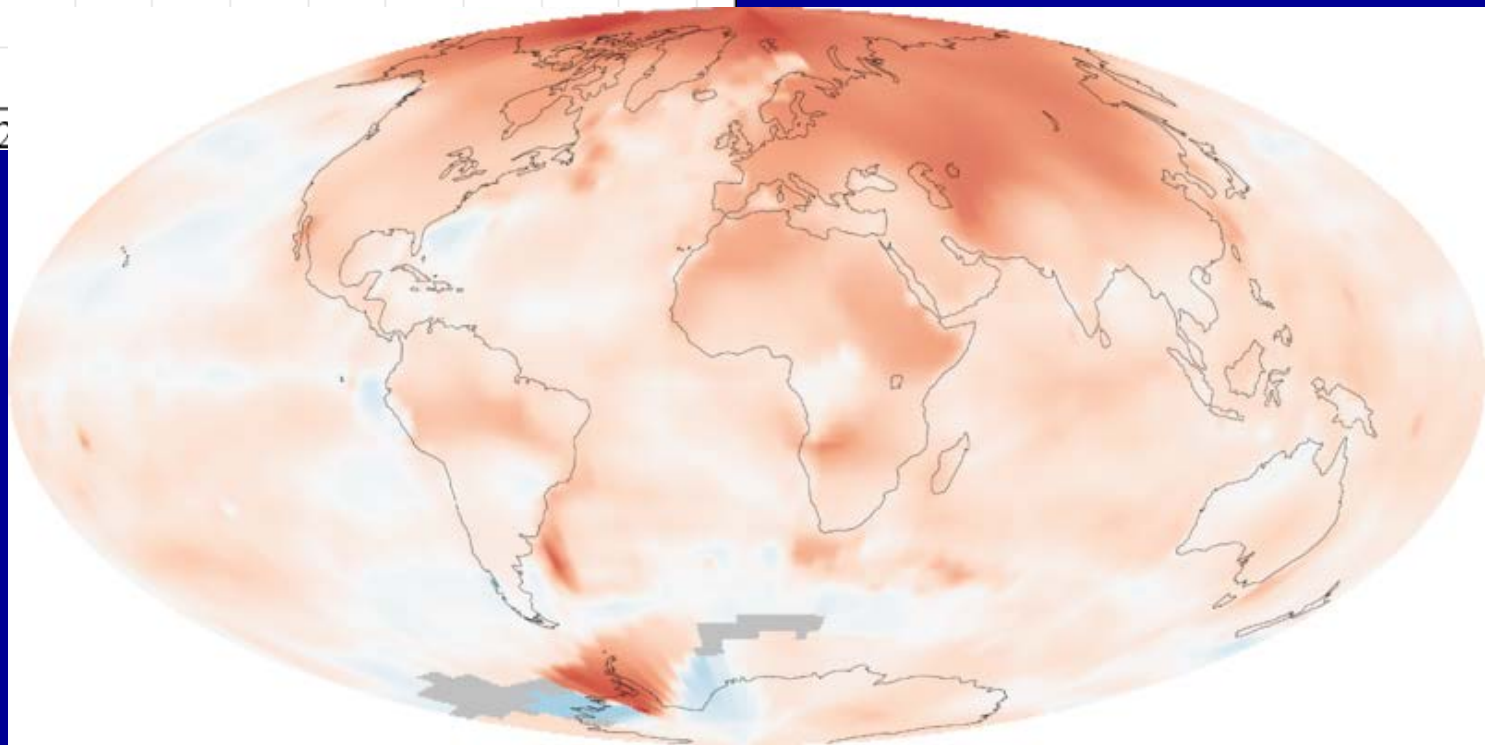
Thanks to: The David and Lucile Packard Foundation!

October 2013



Climate change over the last century





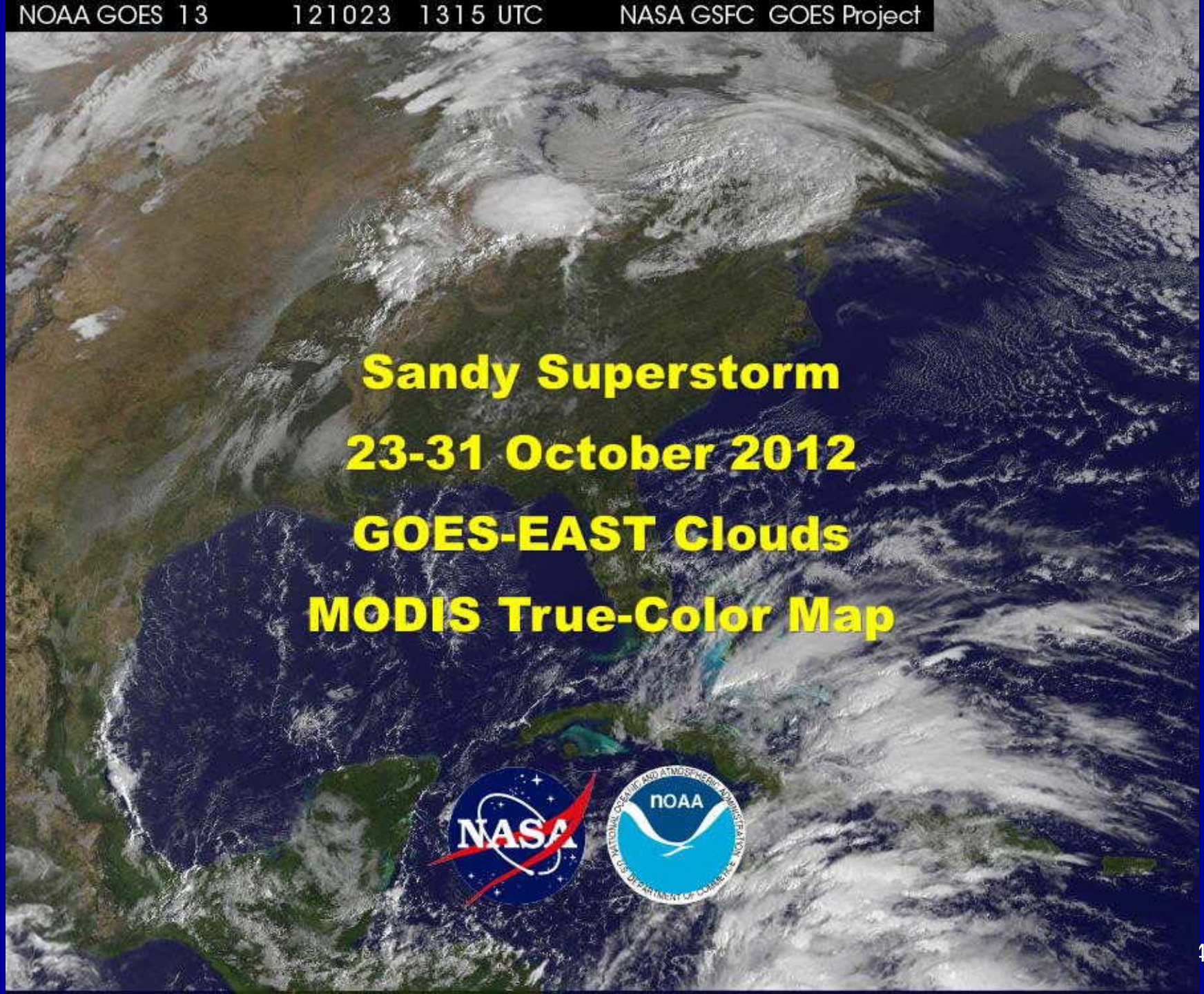
Wikipedia/ NASA

Scientific questions:

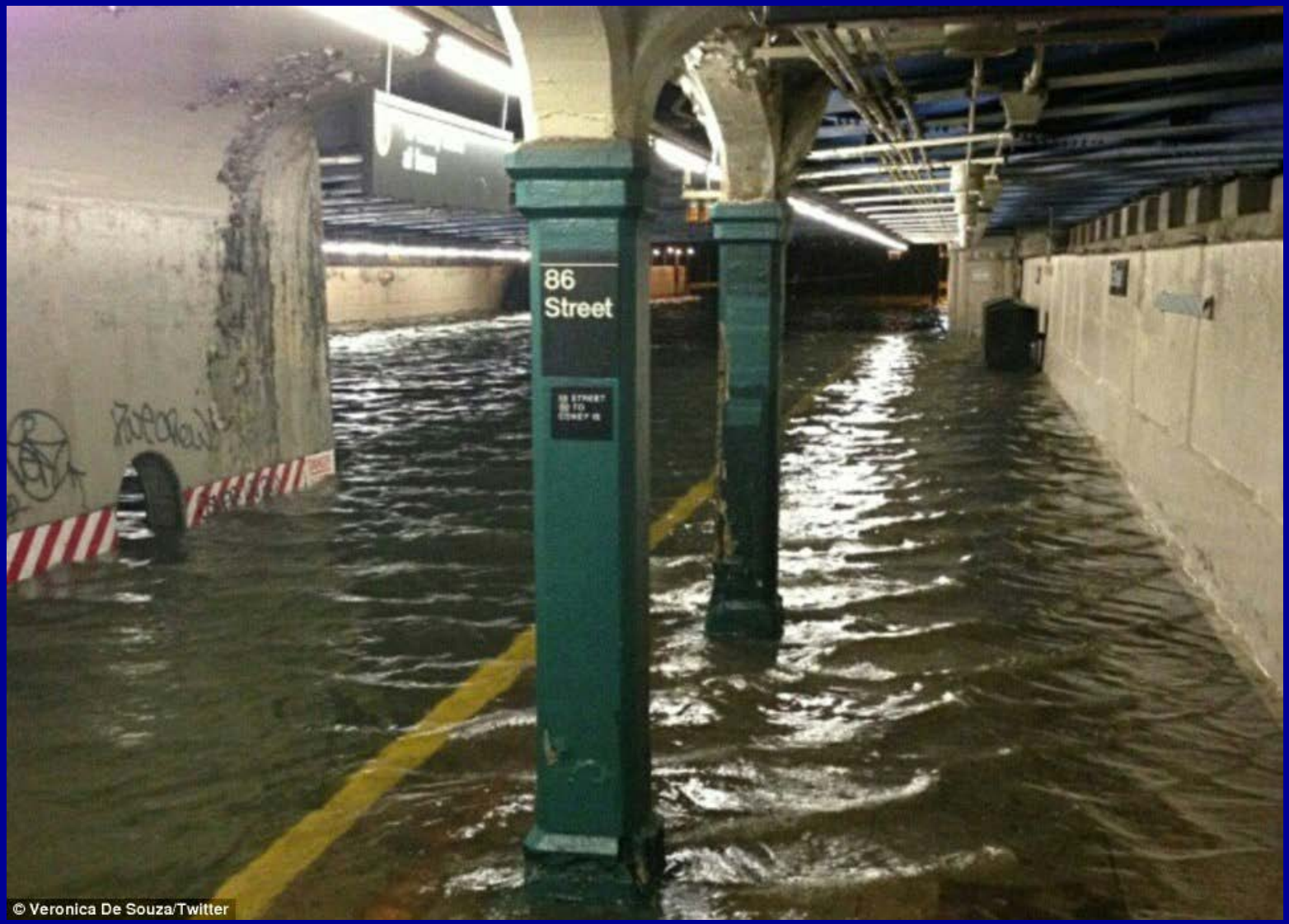
How much will global temperature increase by the end of this century and beyond (climate sensitivity)?

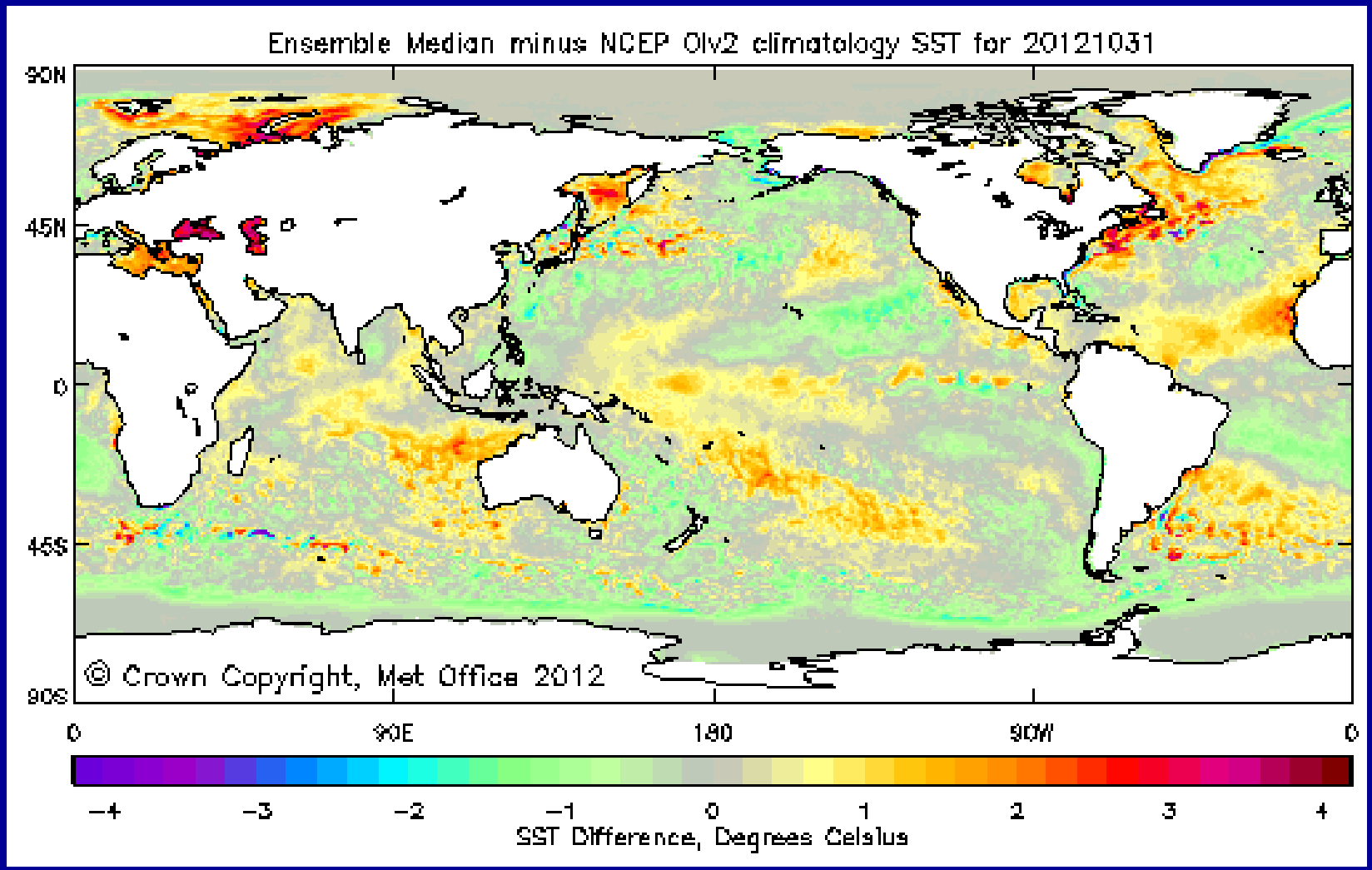
What regional patterns of climate change should we expect?

How will extreme weather events, including tropical cyclones, be affected?

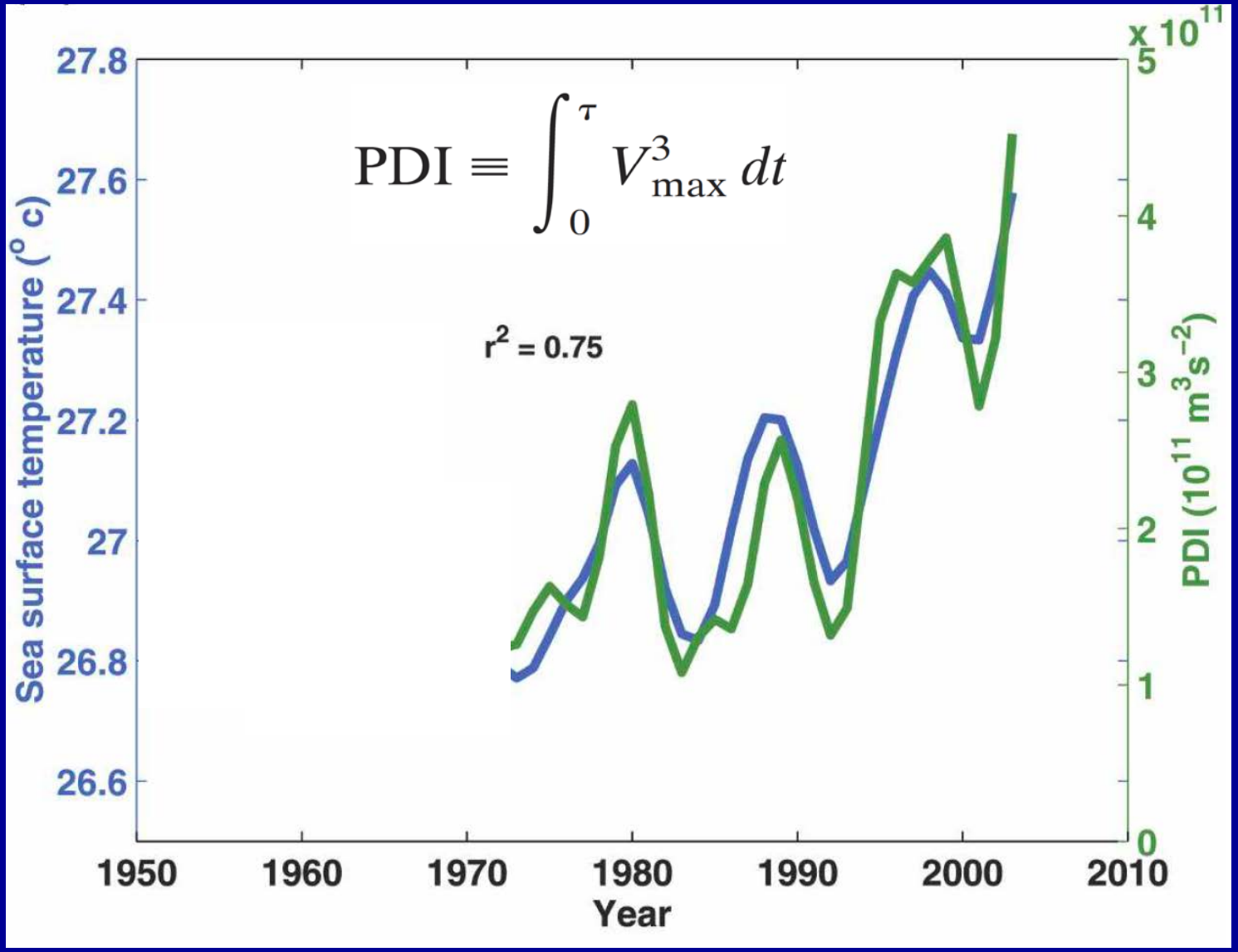

NOAA GOES 13 121023 1315 UTC NASA GSFC GOES Project
Sandy Superstorm
23-31 October 2012
GOES-EAST Clouds
MODIS True-Color Map
NASA
NOAA

Homes are flooded after Hurricane Sandy made landfall on the southern New Jersey coastline in this U.S. Coast Guard handout photo of Tuckerton, New Jersey on Tuesday.


86
Street
© Veronica De Souza/Twitter

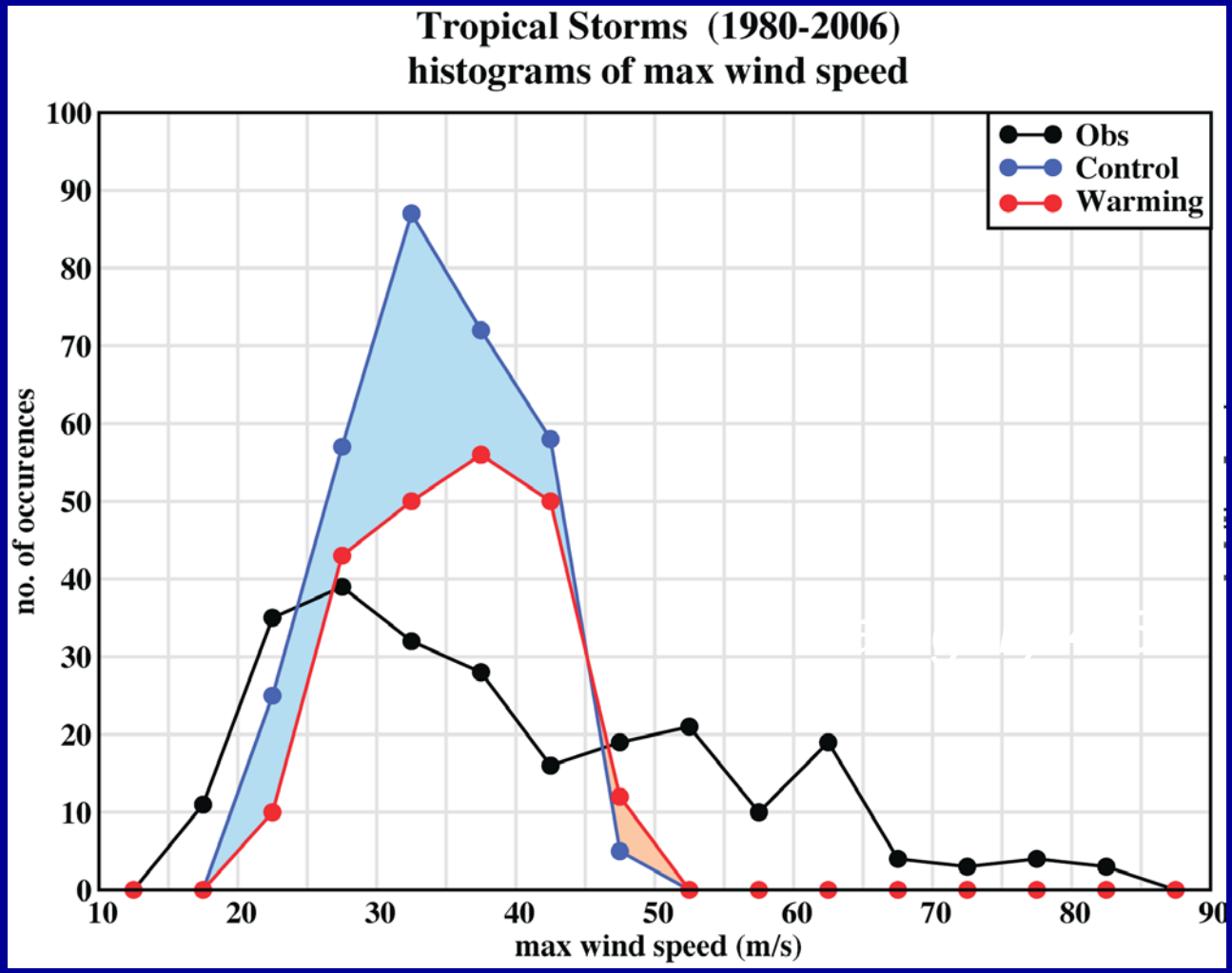

Ensemble Median minus NCEP Olv2 climatology SST for 20121031
90N
45N
0
45S
90S
© Crown Copyright, Met Office 2012
0
90E
180
90W
0
−4
−3
−2
−1
0
1
2
3
4
SST Difference, Degrees Celsius

Power Dissipation Index and Sea Surface Temperatures over the tropical Atlantic



Emanuel 2007

Projections for Atlantic hurricanes (Aug-Oct)



Black curve: observed distribution

Blue curve: the simulated distribution for present-day climate

Red curve: the simulated distribution for the late 21st century (A1B forcing) A regional dynamical downscaling model of Knutson et al. (2008)

This talk:

What could we learn from past climates (the early Pliocene epoch) and idealized climate simulations to inform our understanding of global warming and its impacts on tropical cyclones?

ARTICLE

doi:10.1038/nature12003

Patterns and mechanisms of early Pliocene warmth

A. V. Fedorov[1]*, C. M. Brierley[1,2]*, K. T. Lawrence[3]*, Z. Liu[4], P. S. Dekens[5] & A. C. Ravelo[6]

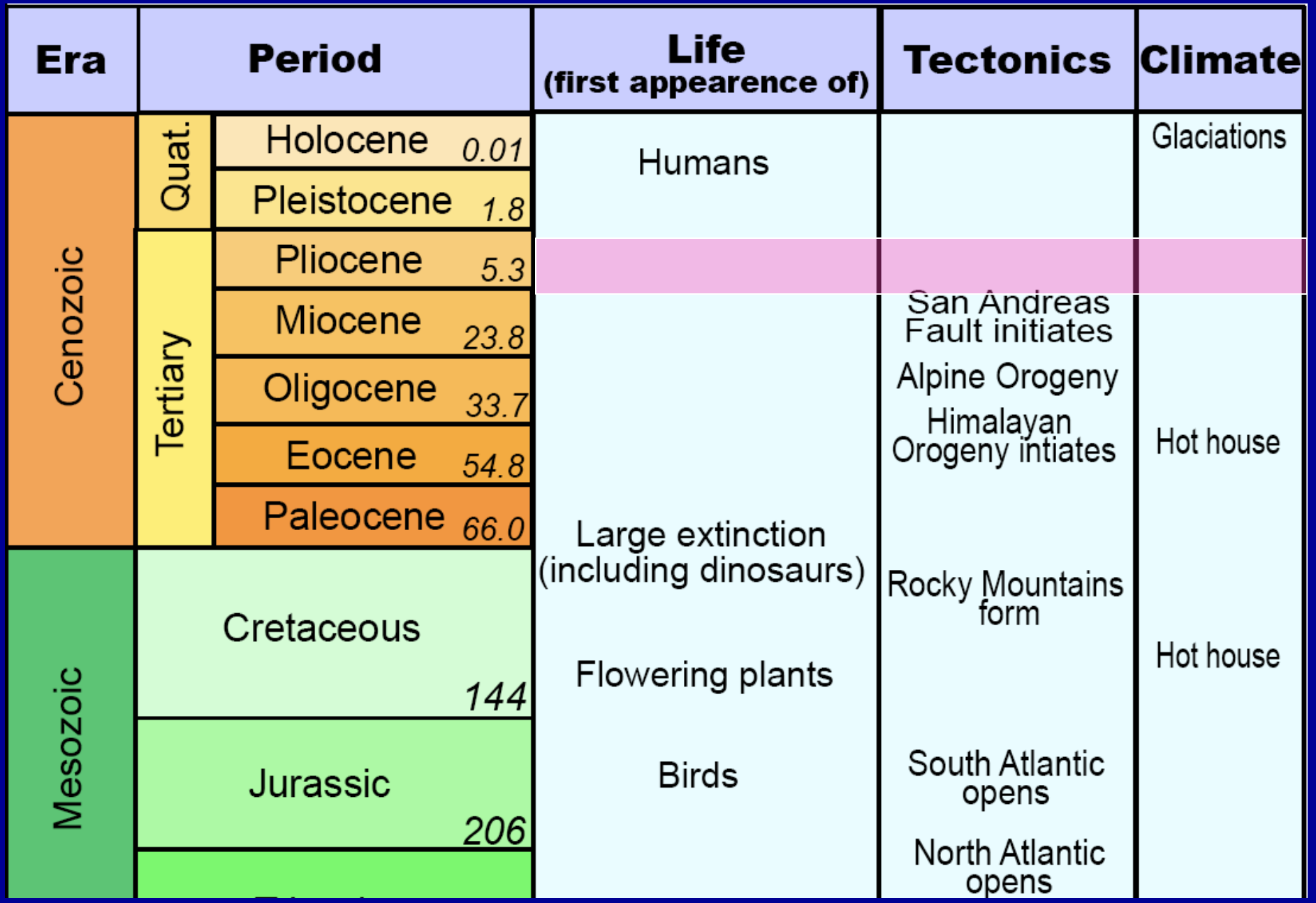
nature Vol 463|25 February 2010|doi:10.1038/nature08831

LETTERS

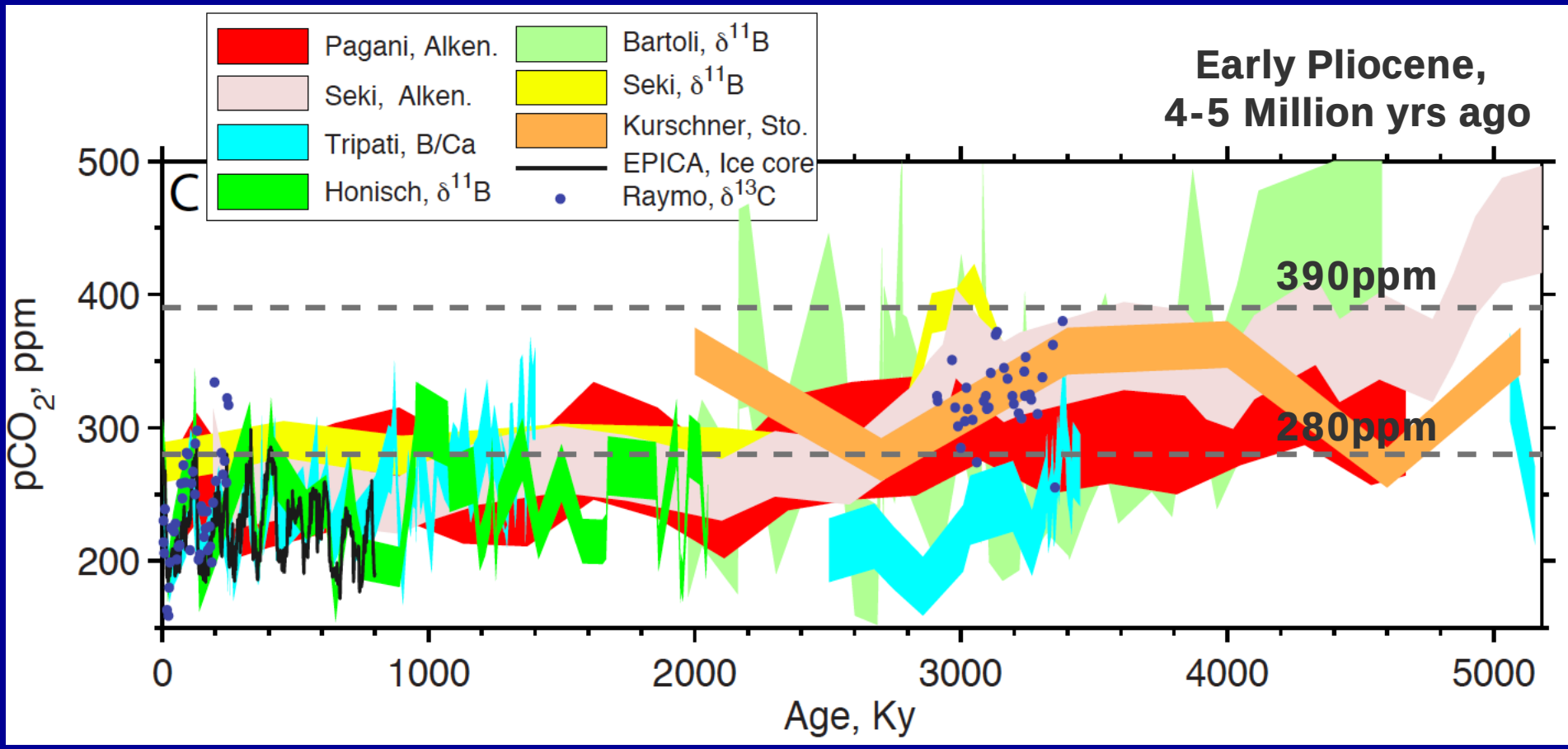
Tropical cyclones and permanent El Niño in the early Pliocene epoch

Alexey V. Fedorov[1], Christopher M. Brierley[1] & Kerry Emanuel[2]

Simulations of tropical cyclones with a cloud-system resolving model for different climates (in prep.) 2013
A.V. Fedorov, L. Muir and W. Boos


Era
Period
Life
(first appearence of)
Tectonics
Climate
Cenozoic
Quat.
Holocene 0.01
Pleistocene 1.8
Tertiary
Pliocene 5.3
Miocene 23.8
Oligocene 33.7
Eocene 54.8
Paleocene 66.0
Mesozoic
Cretaceous 144
Jurassic 206
Humans
Large extinction
(including dinosaurs)
Flowering plants
Birds
San Andreas
Fault initiates
Alpine Orogeny
Himalayan
Orogeny intiates
Rocky Mountains
form
South Atlantic
opens
North Atlantic
opens
Glaciations
Hot house
Hot house

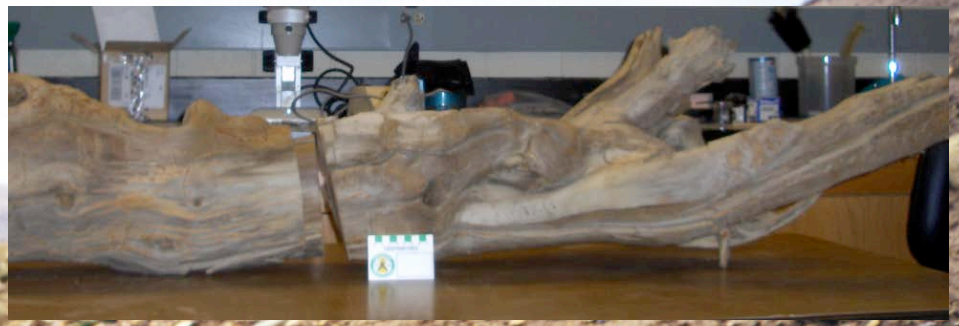
Elevated CO_2 in the Pliocene

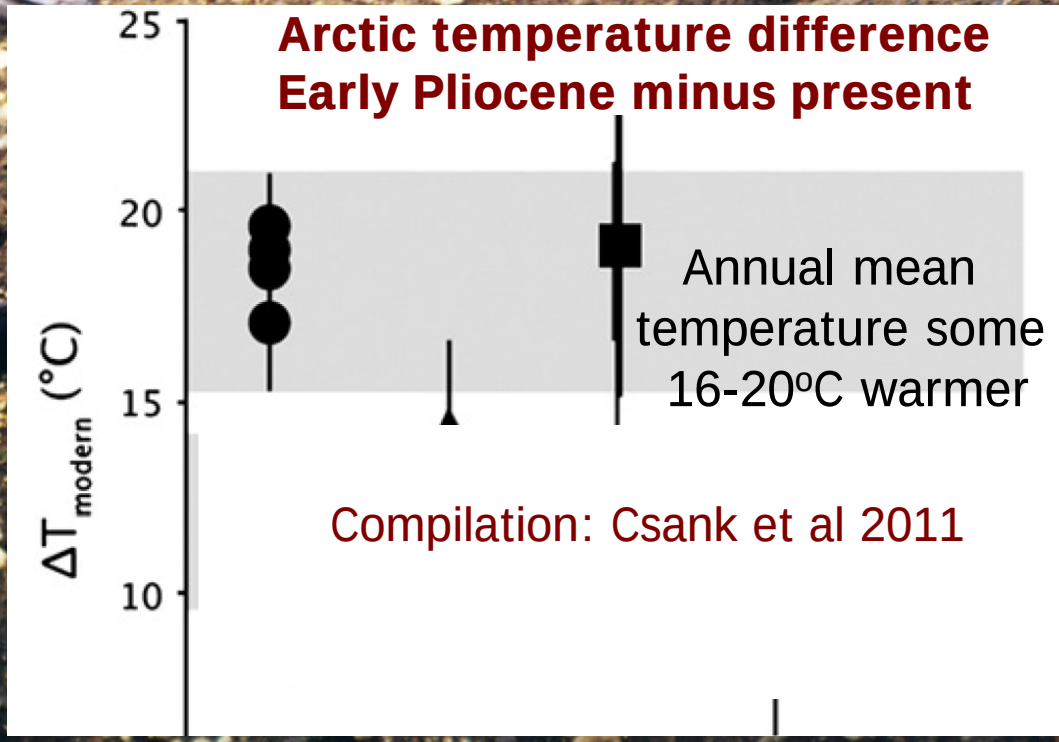


Fedorov, Lawrence, Brierley, Liu, Dekens, Ravelo 2013 – Nature

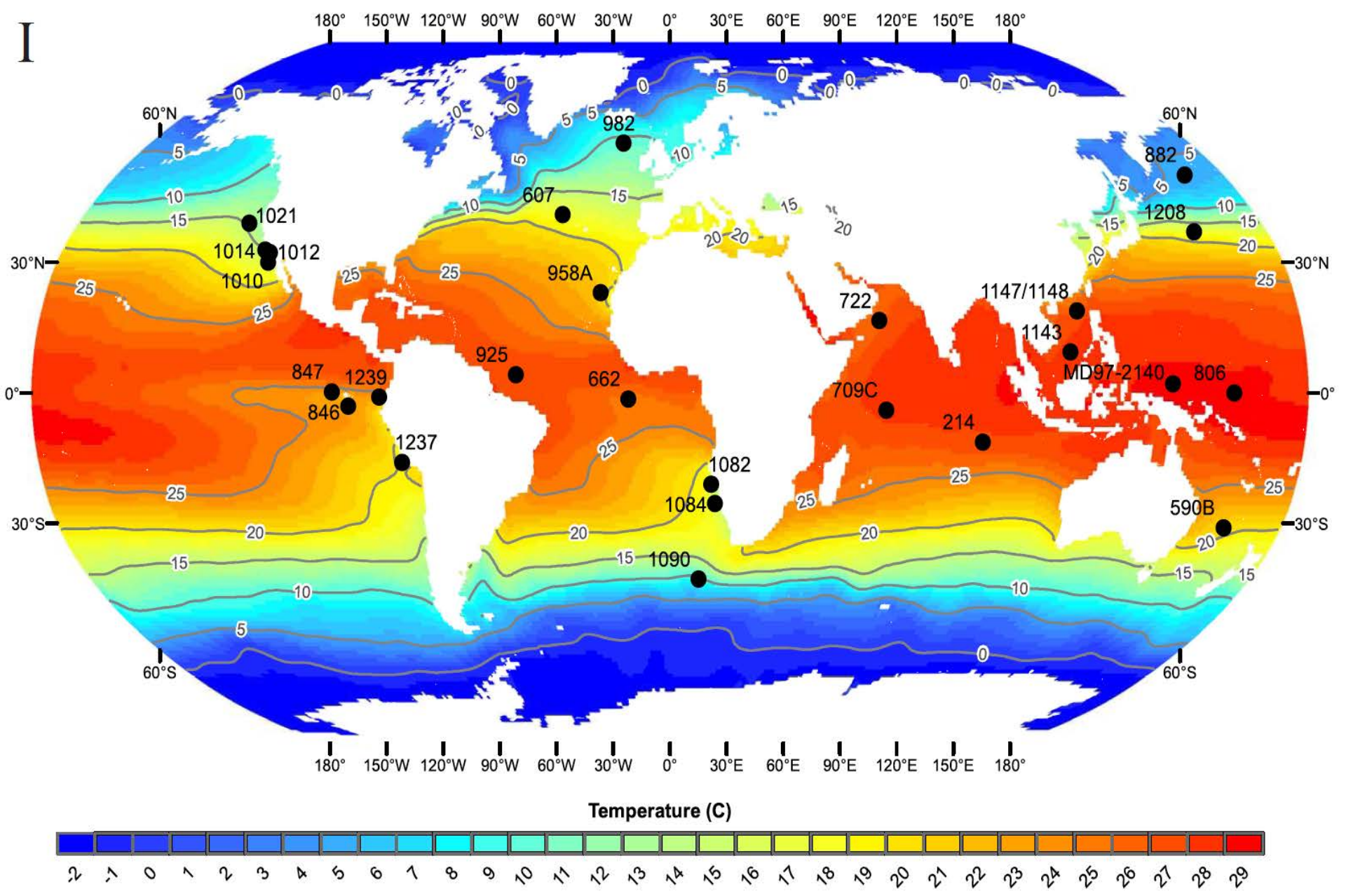
Ellesmere Island, 78ºN

Fossil tree trunks and leaves from the early Pliocene (4-5Ma) in high Arctic, Csank et al 2011

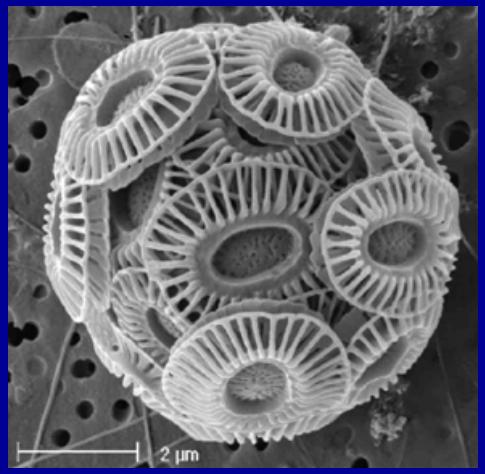




Climate evolution of the past 5 million years



Fedorov, Brierley, Lawrence, Dekens, Liu, Ravelo 2013, Nature



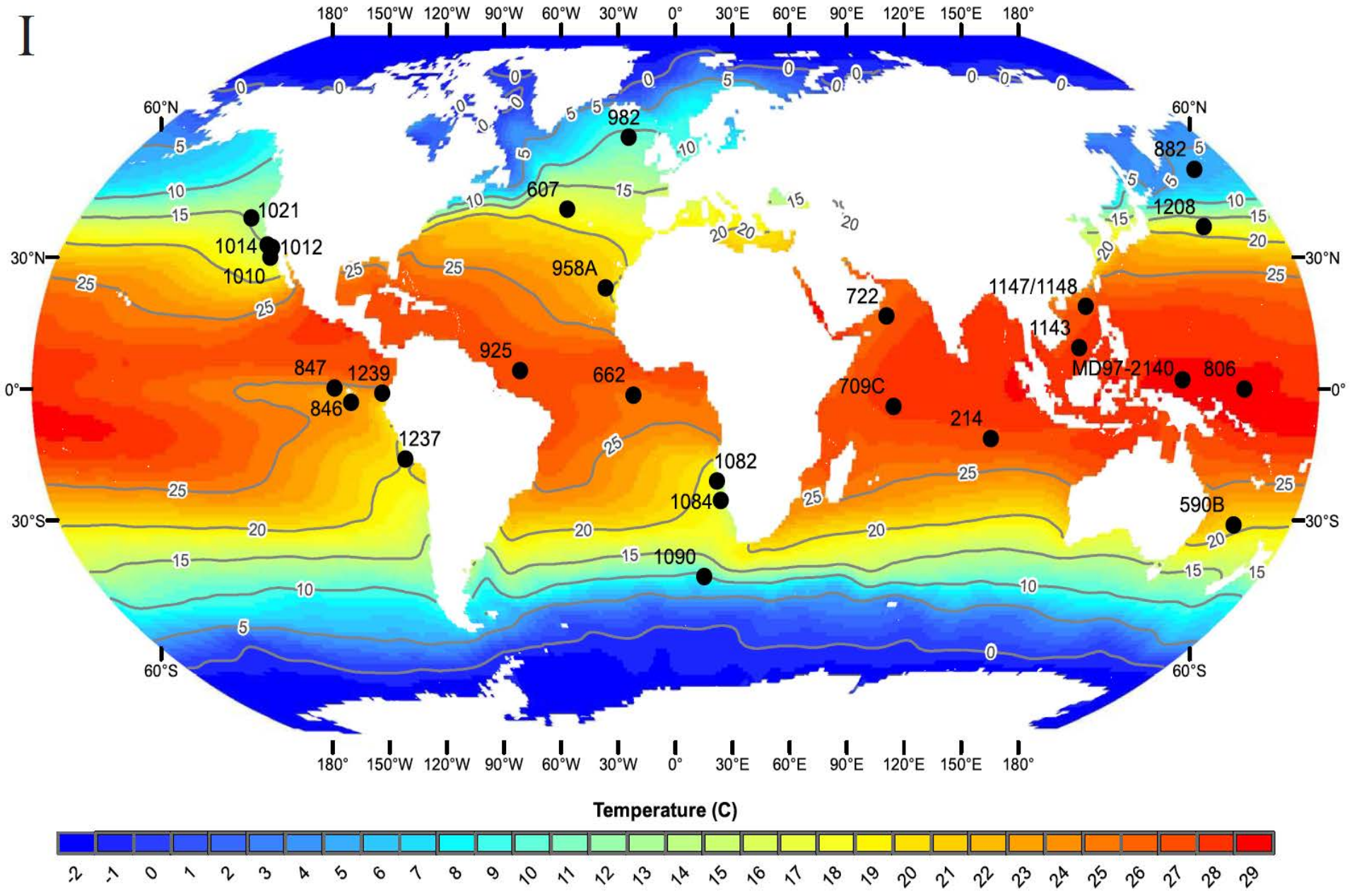
2 µm

1 mm

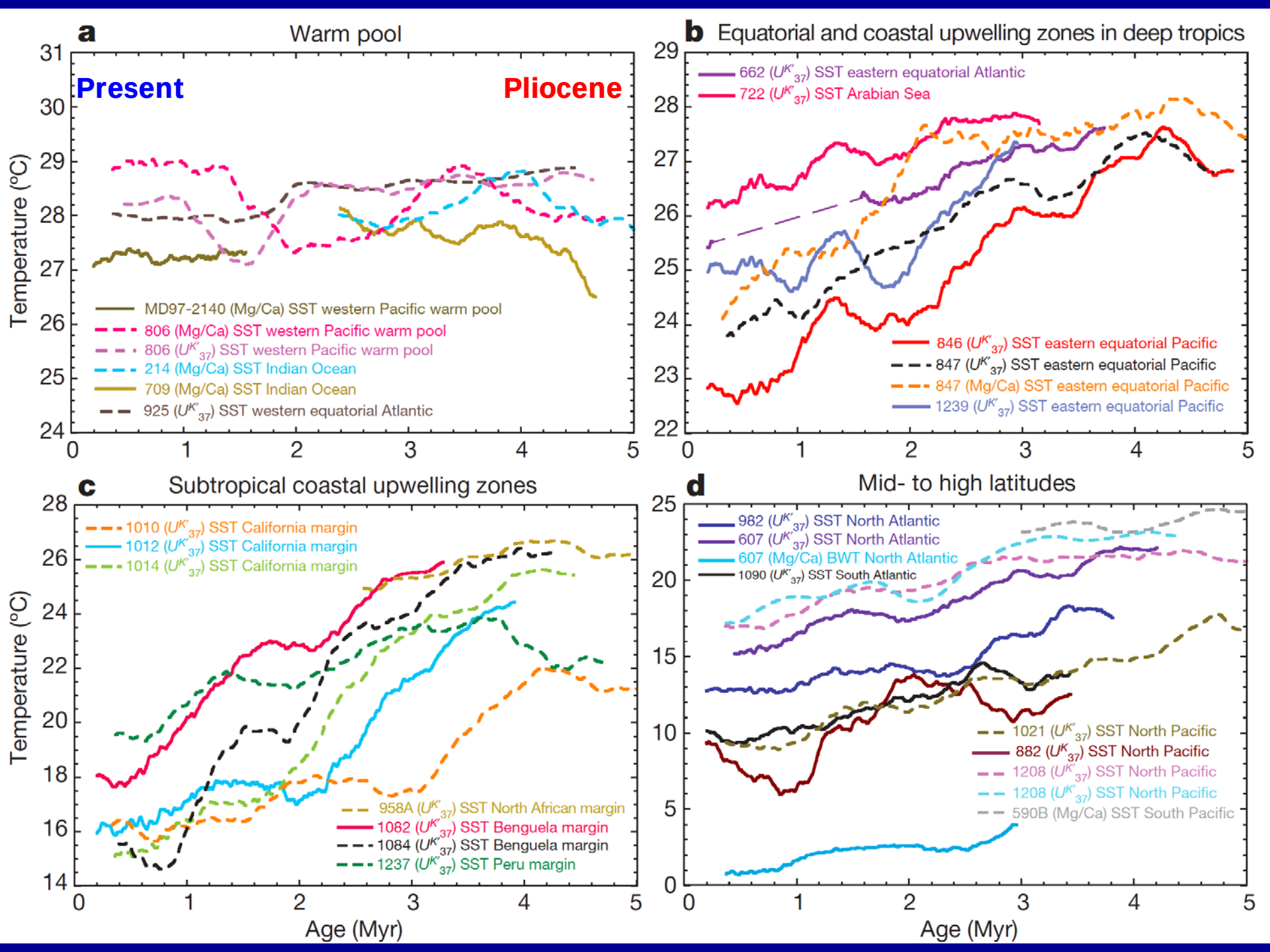
Alkenone *unsaturation ratio in organic compounds produced by phytoplankton (coccolithophorid Emiliana huxleyi)*

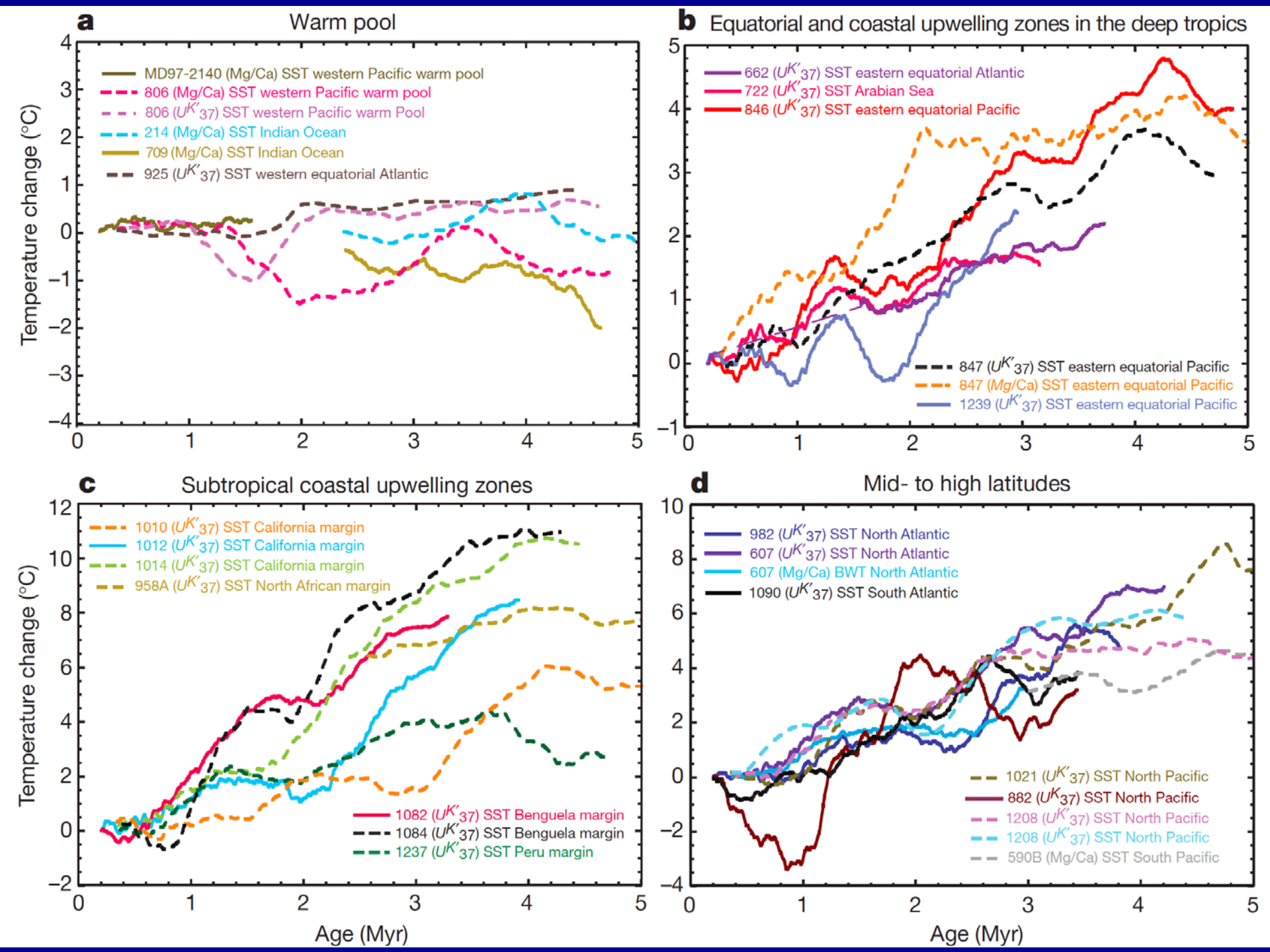
Mg/Ca ratio *in the fossil shells of foraminifers*

Climate evolution of the past 5 million years

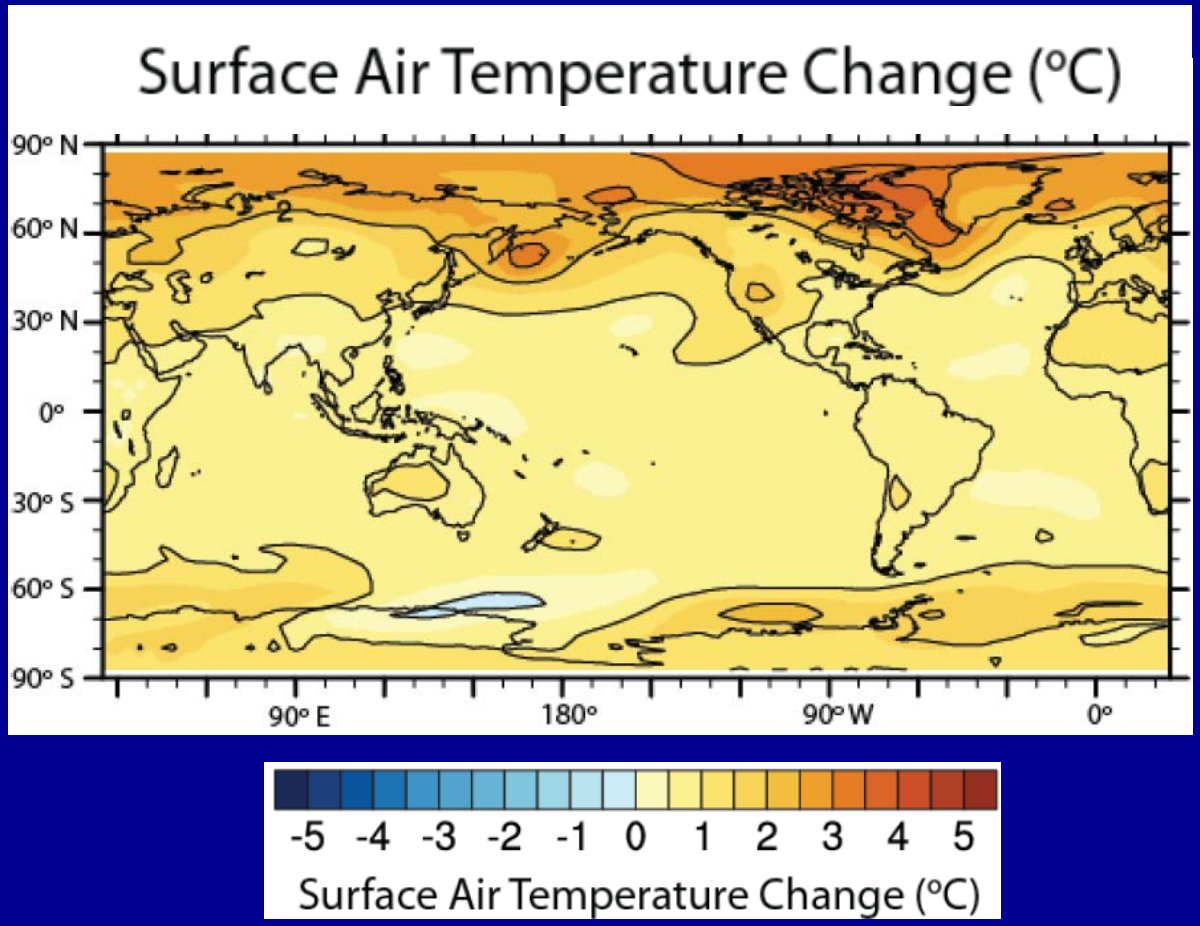


Fedorov, Brierley, Lawrence, Dekens, Liu, Ravelo 2013, Nature


a
Warm pool
Present
Pliocene
Temperature (°C)
MD97-2140 (Mg/Ca) SST western Pacific warm pool
806 (Mg/Ca) SST western Pacific warm pool
806 ($U^{K'}_{37}$) SST western Pacific warm pool
214 (Mg/Ca) SST Indian Ocean
709 (Mg/Ca) SST Indian Ocean
925 ($U^{K'}_{37}$) SST western equatorial Atlantic
b
Equatorial and coastal upwelling zones in deep tropics
662 ($U^{K'}_{37}$) SST eastern equatorial Atlantic
722 ($U^{K'}_{37}$) SST Arabian Sea
846 ($U^{K'}_{37}$) SST eastern equatorial Pacific
847 ($U^{K'}_{37}$) SST eastern equatorial Pacific
847 (Mg/Ca) SST eastern equatorial Pacific
1239 ($U^{K'}_{37}$) SST eastern equatorial Pacific
c
Subtropical coastal upwelling zones
1010 ($U^{K'}_{37}$) SST California margin
1012 ($U^{K'}_{37}$) SST California margin
1014 ($U^{K'}_{37}$) SST California margin
958A ($U^{K'}_{37}$) SST North African margin
1082 ($U^{K'}_{37}$) SST Benguela margin
1084 ($U^{K'}_{37}$) SST Benguela margin
1237 ($U^{K'}_{37}$) SST Peru margin
Temperature (°C)
Age (Myr)
d
Mid- to high latitudes
982 ($U^{K'}_{37}$) SST North Atlantic
607 ($U^{K'}_{37}$) SST North Atlantic
607 (Mg/Ca) BWT North Atlantic
1090 ($U^{K'}_{37}$) SST South Atlantic
1021 ($U^{K'}_{37}$) SST North Pacific
882 ($U^{K'}_{37}$) SST North Pacific
1208 ($U^{K'}_{37}$) SST North Pacific
1208 ($U^{K'}_{37}$) SST North Pacific
590B (Mg/Ca) SST South Pacific
Age (Myr)

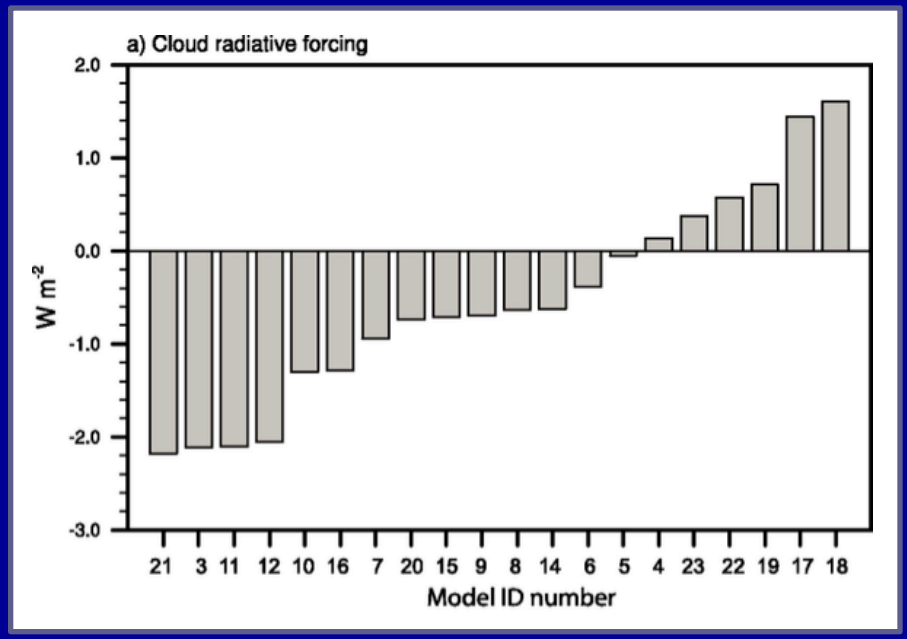

a
Warm pool
Temperature change (°C)
MD97-2140 (Mg/Ca) SST western Pacific warm pool
806 (Mg/Ca) SST western Pacific warm pool
806 ($U^{K'}_{37}$) SST western Pacific warm Pool
214 (Mg/Ca) SST Indian Ocean
709 (Mg/Ca) SST Indian Ocean
925 ($U^{K'}_{37}$) SST western equatorial Atlantic
b
Equatorial and coastal upwelling zones in the deep tropics
662 ($U^{K'}_{37}$) SST eastern equatorial Atlantic
722 ($U^{K'}_{37}$) SST Arabian Sea
846 ($U^{K'}_{37}$) SST eastern equatorial Pacific
847 ($U^{K'}_{37}$) SST eastern equatorial Pacific
847 (Mg/Ca) SST eastern equatorial Pacific
1239 ($U^{K'}_{37}$) SST eastern equatorial Pacific
c
Subtropical coastal upwelling zones
Temperature change (°C)
1010 ($U^{K'}_{37}$) SST California margin
1012 ($U^{K'}_{37}$) SST California margin
1014 ($U^{K'}_{37}$) SST California margin
958A ($U^{K'}_{37}$) SST North African margin
1082 ($U^{K'}_{37}$) SST Benguela margin
1084 ($U^{K'}_{37}$) SST Benguela margin
1237 ($U^{K'}_{37}$) SST Peru margin
Age (Myr)
d
Mid- to high latitudes
982 ($U^{K'}_{37}$) SST North Atlantic
607 ($U^{K'}_{37}$) SST North Atlantic
607 (Mg/Ca) BWT North Atlantic
1090 ($U^{K'}_{37}$) SST South Atlantic
1021 ($U^{K'}_{37}$) SST North Pacific
882 (U^{K}_{37}) SST North Pacific
1208 ($U^{K'}_{37}$) SST North Pacific
1208 ($U^{K'}_{37}$) SST North Pacific
590B (Mg/Ca) SST South Pacific
Age (Myr)

A big problem: Even a 100ppm CO_2 increase within climate models is insufficient to simulate the observed warmth of the early Pliocene!

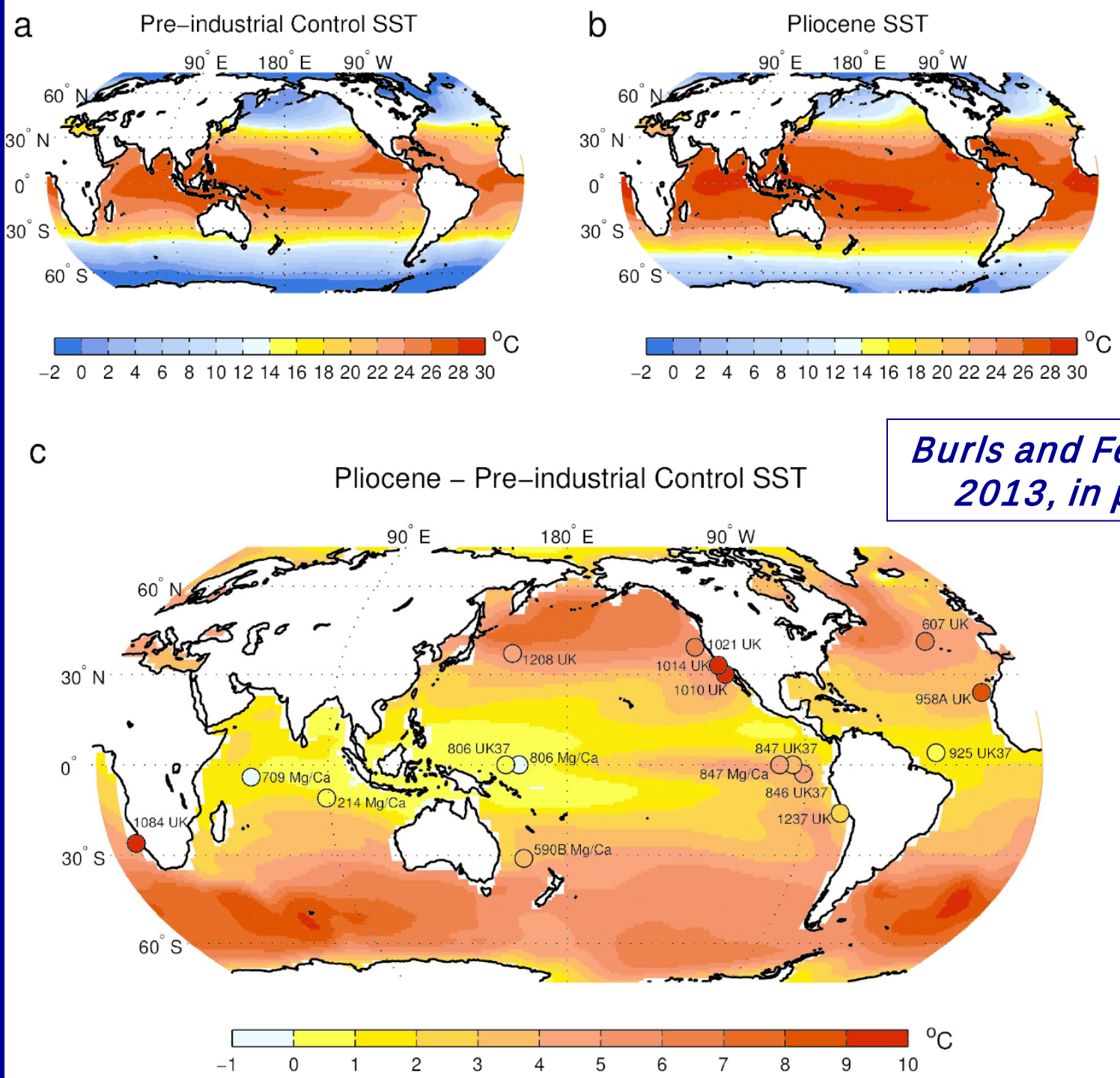


Cloud Feedbacks

- Cloud properties and feedbacks are the largest cause of uncertainty in climate projections



IPCC AR4: Global mean cloud radiative forcing from coupled models under A1B scenario – not even the sign is certain !

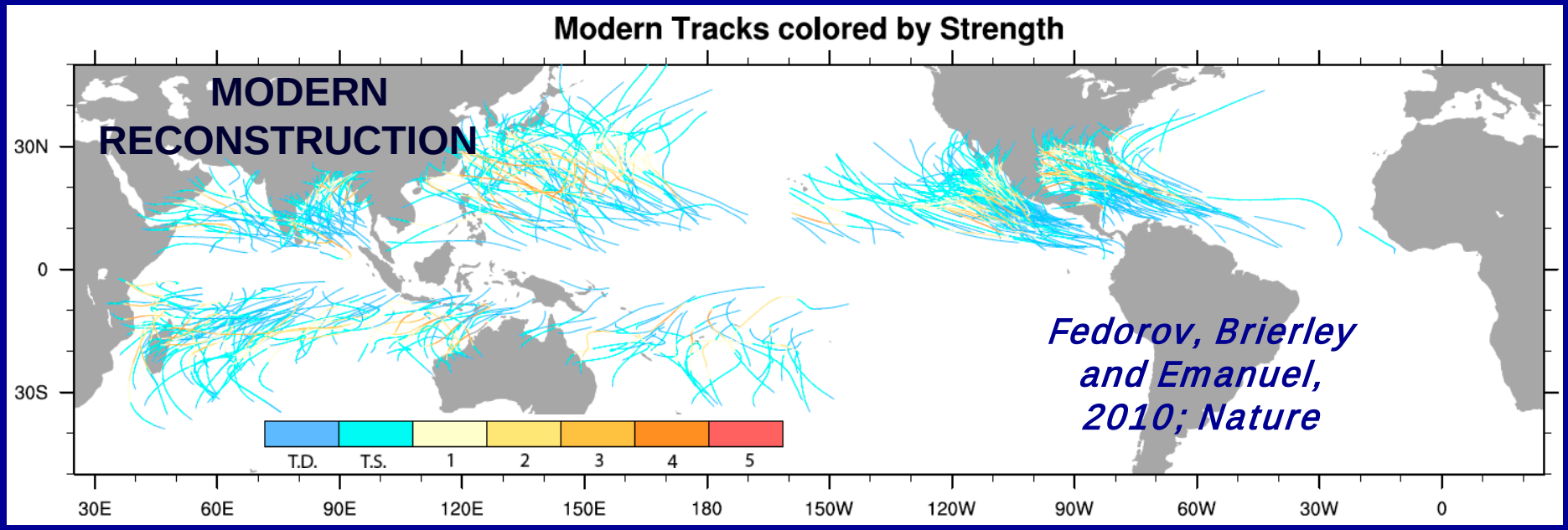


Burls and Fedorov 2013, in prep

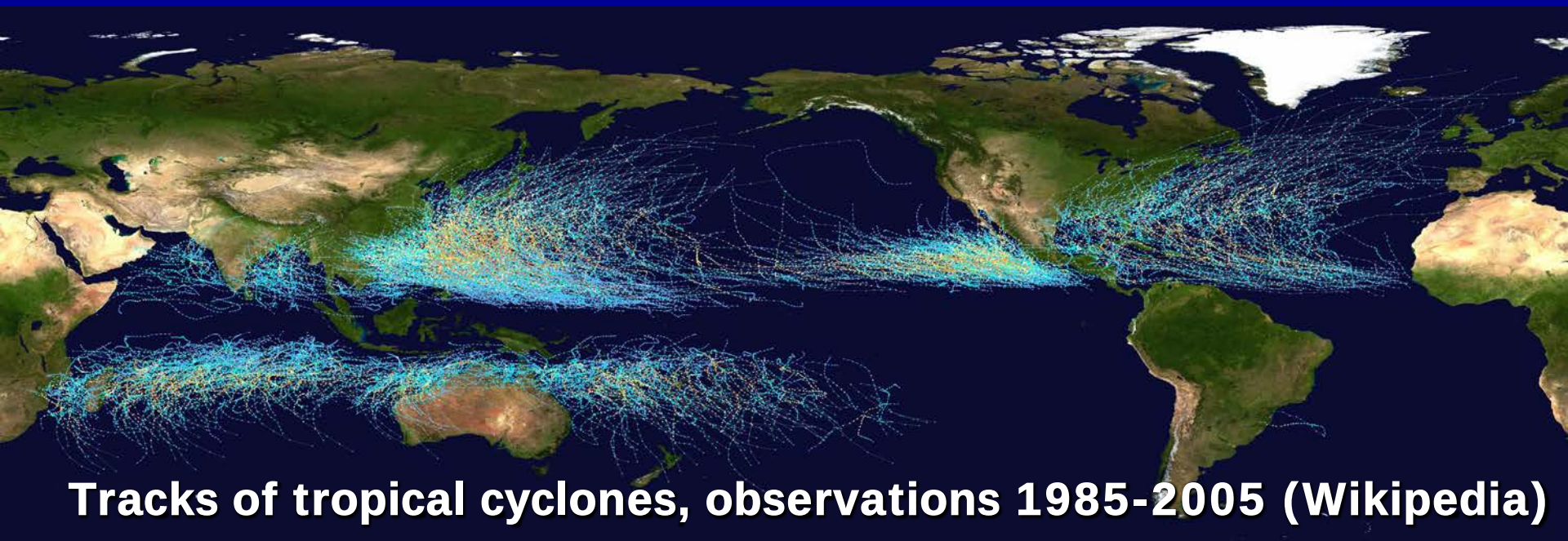
Hurricane Statistical Downscaling Model (SDSM)

- *Described in Emanuel 2006*
- *Generates synthetic hurricane tracks*
- *Takes into account large-scale atmospheric fields (sea surface temperature, lapse rates, specific humidity, wind shear), which can be computed from a large-scale atmospheric GCM*
- *Hurricanes are initiated by random seeding (inserting weak vortices)*

Hurricane Statistical Downscaling Model (SDSM)

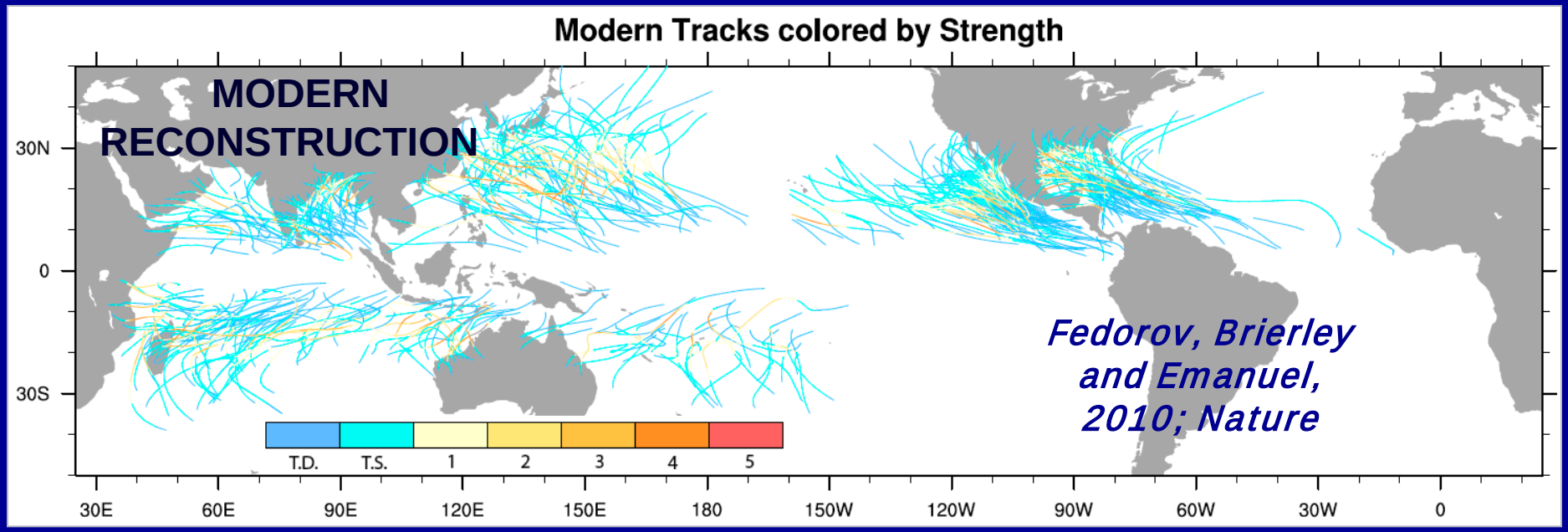


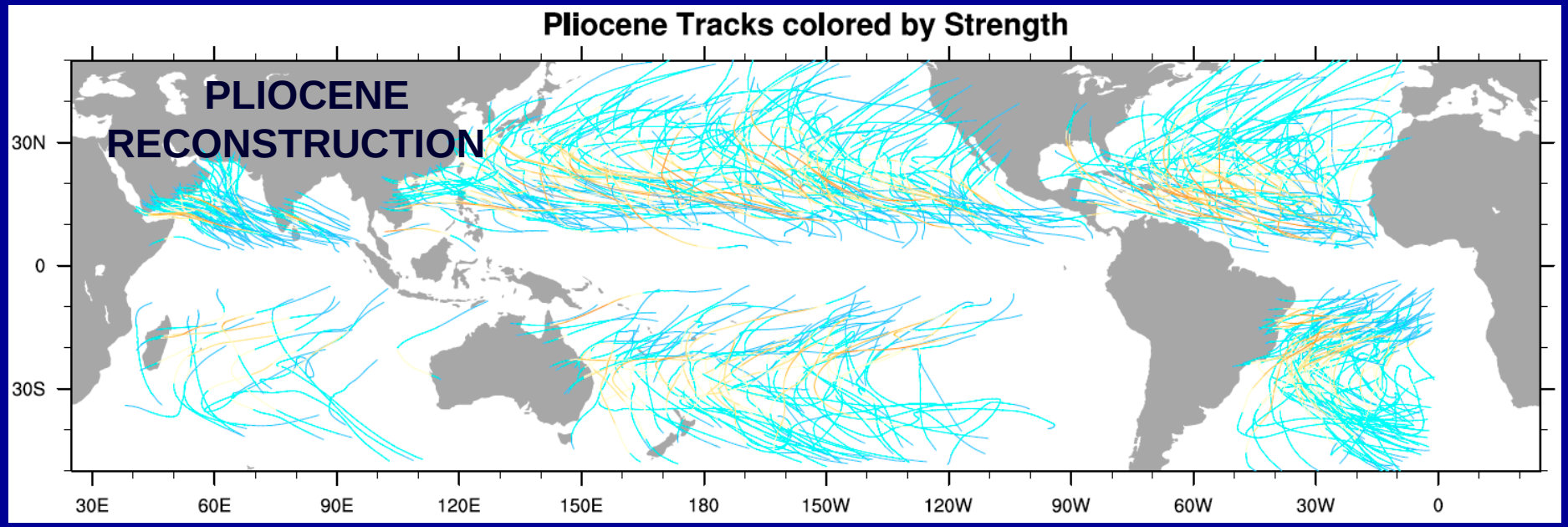
Fedorov, Brierley and Emanuel, 2010; Nature

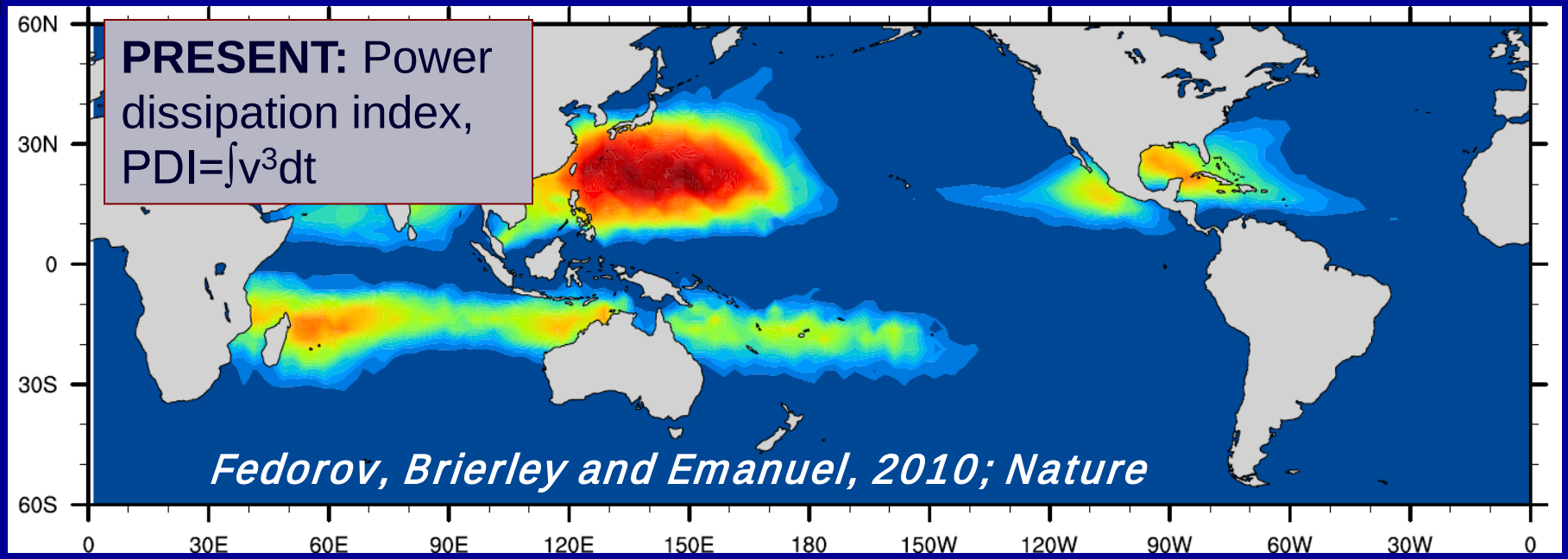


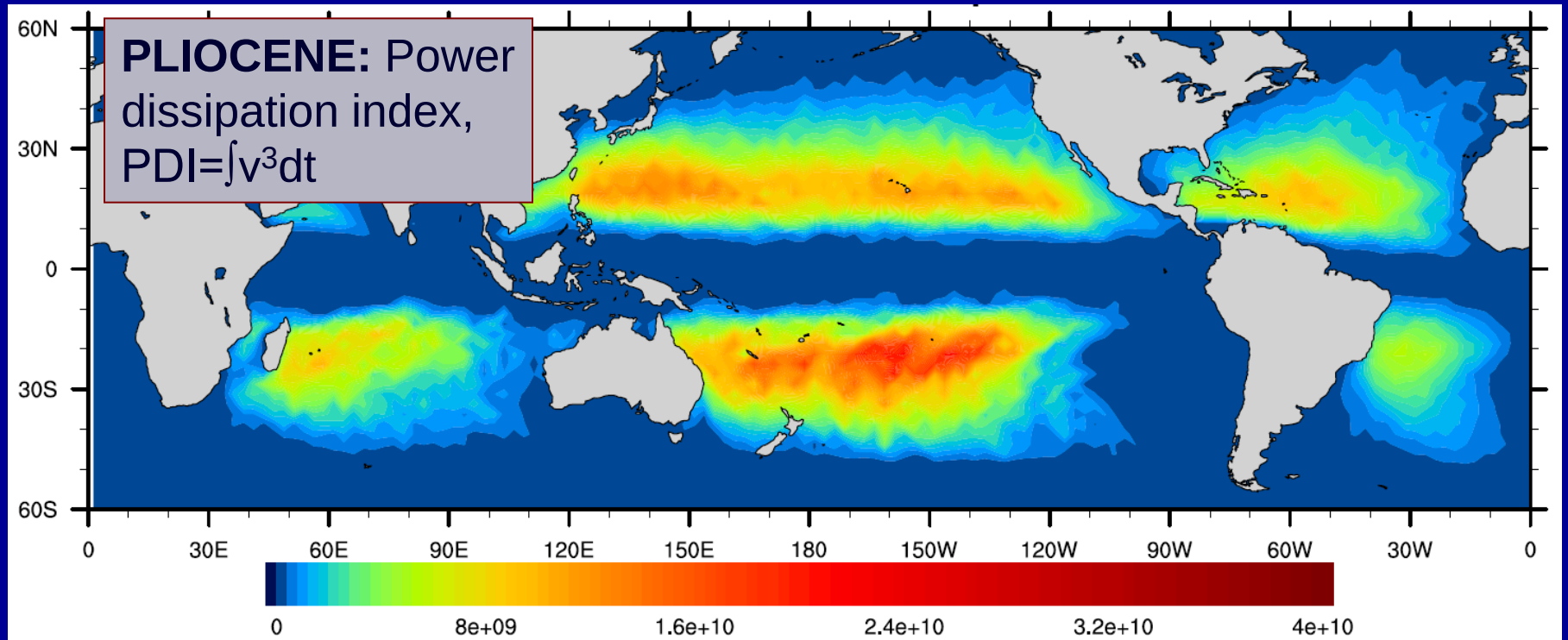
Tracks of tropical cyclones, observations 1985-2005 (Wikipedia)

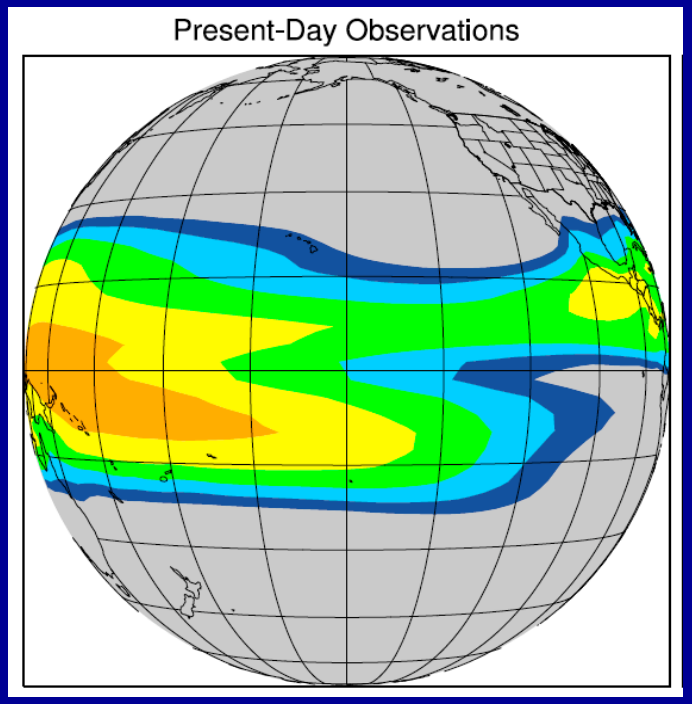
Hurricane Statistical Downscaling Model (SDSM)





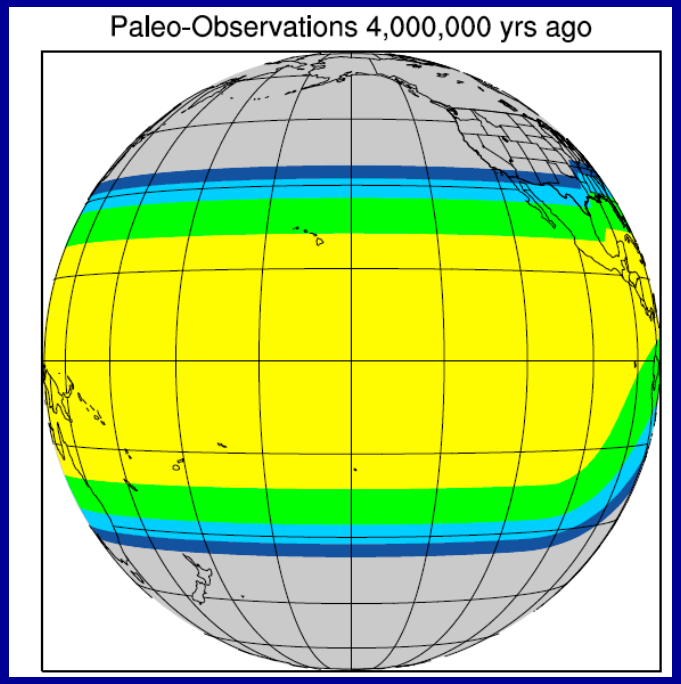

PRESENT: Power dissipation index, PDI=∫v³dt
Fedorov, Brierley and Emanuel, 2010; Nature
60N
30N
0
30S
60S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0

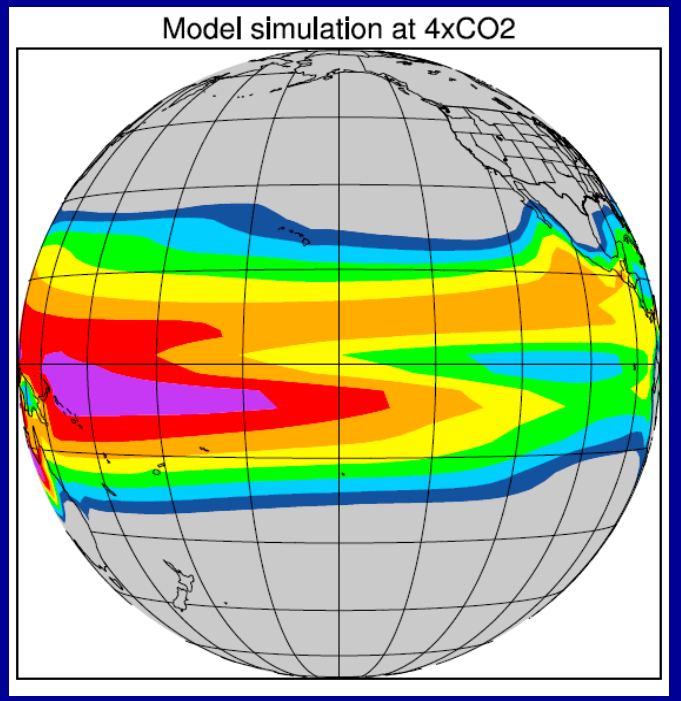

PLIOCENE: Power dissipation index, PDI=∫v³dt
60N
30N
0
30S
60S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
0
8e+09
1.6e+10
2.4e+10
3.2e+10
4e+10

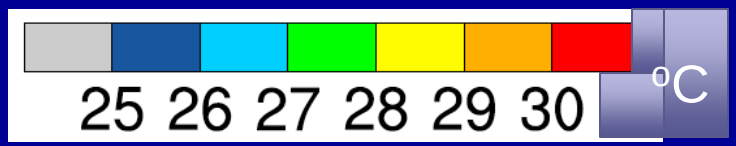


Pliocene

CO_2 x 4







Sensitivity experiments:

Model: SAM = System for Atmospheric Modeling

- ✧ Cloud System or Cloud Resolving Model, Khairoutdinov and Randall 2003
- ✧ Aqua-planet, 1/4 of the globe
- ✧ Resolution: 15km

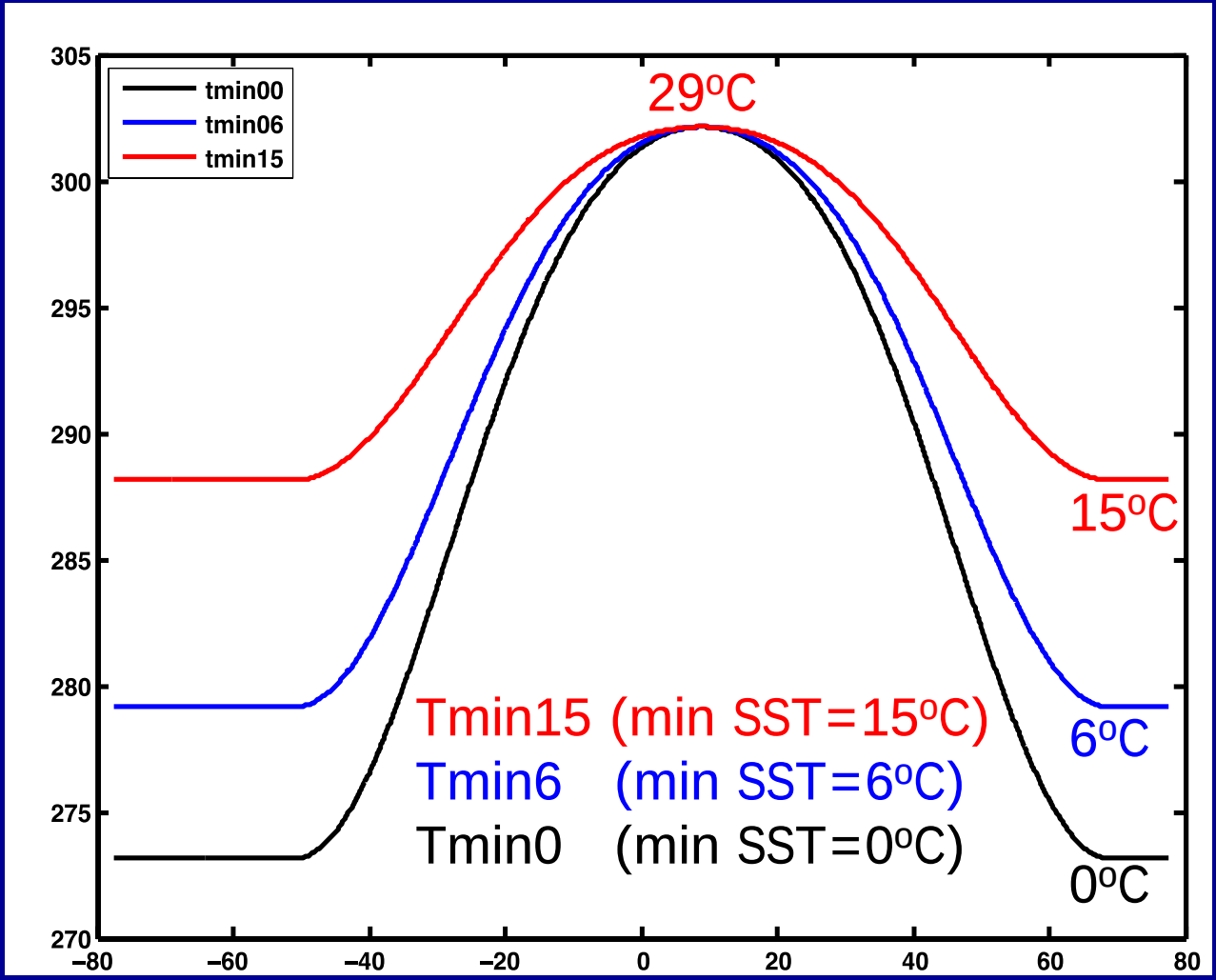
Prescribed SST
(perpetual summer)

Experiments:

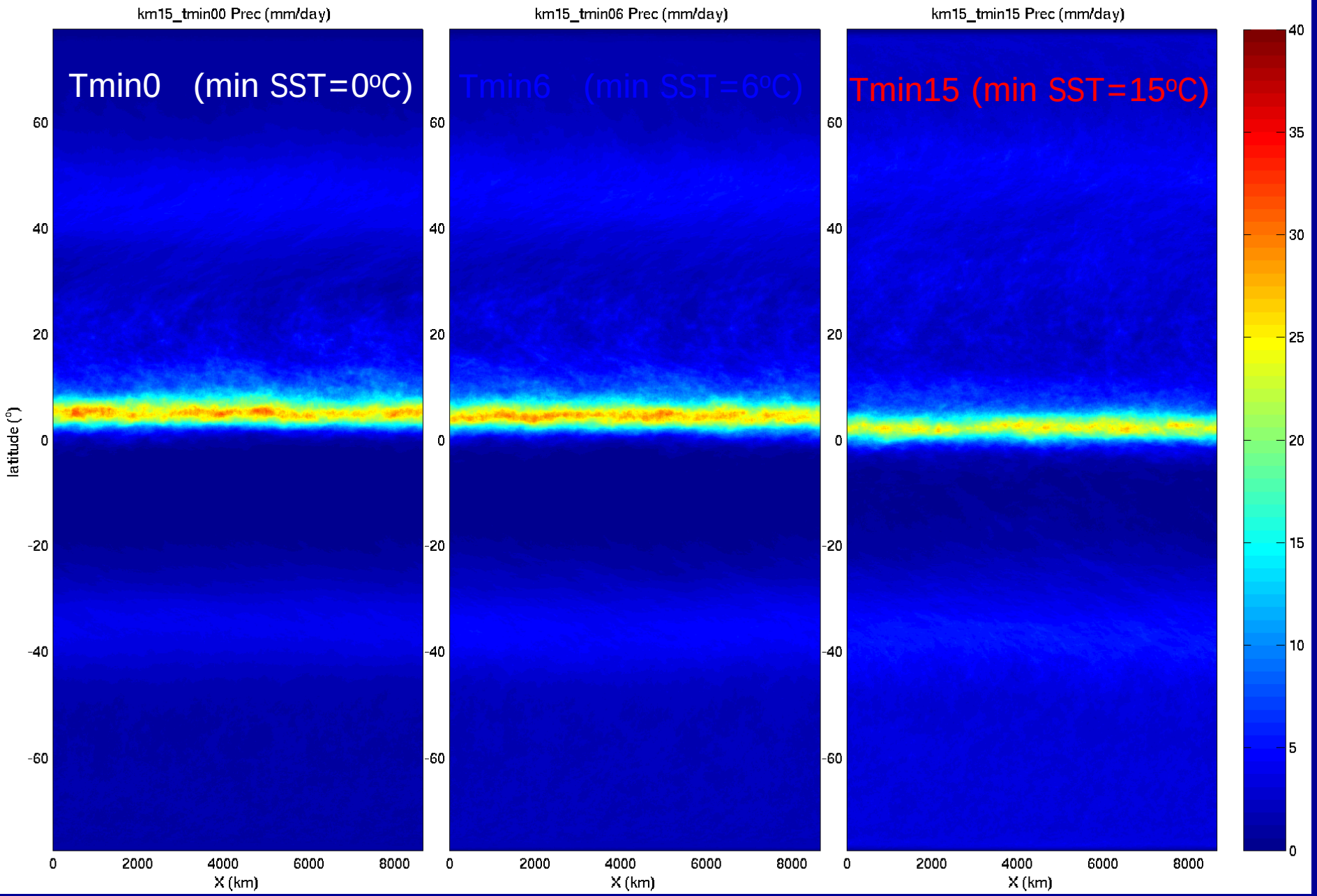
Tmin15 (min SST=15ºC)
Tmin6 (min SST=6ºC)
Tmin0 (min SST=0ºC)

Duration:

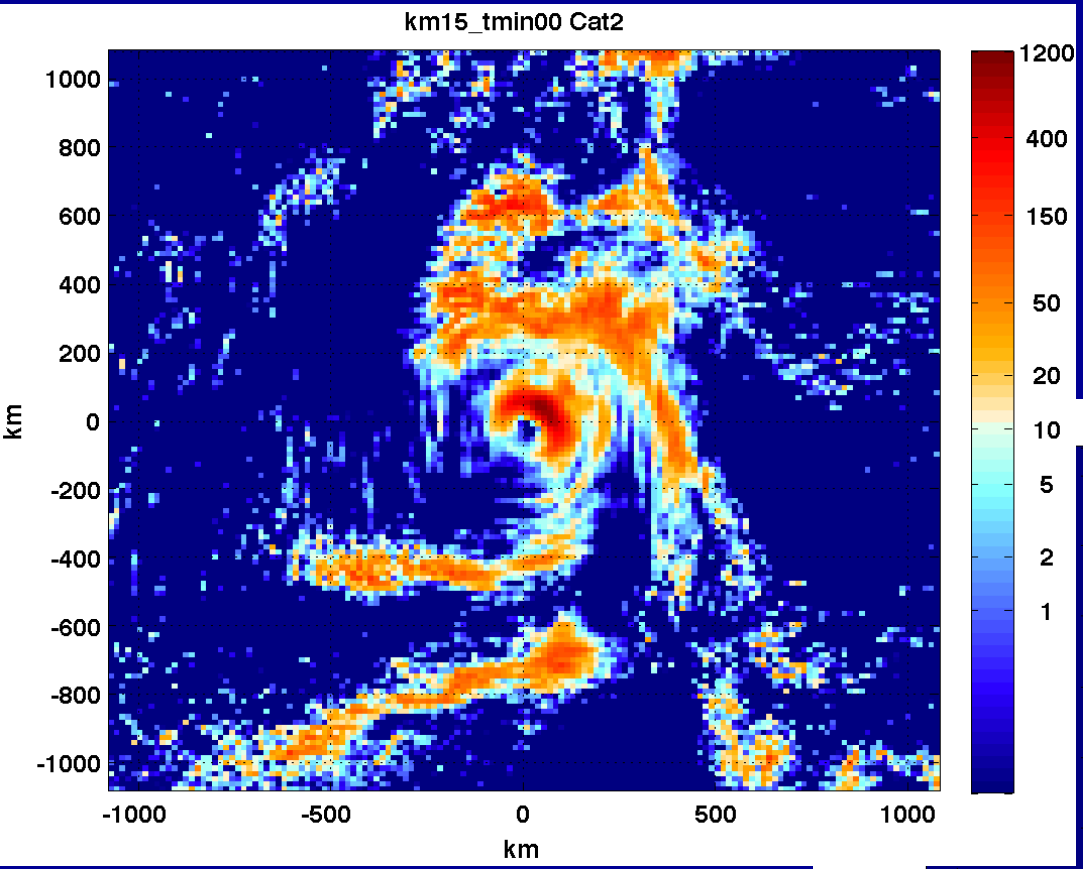
1800 days
(20 seasons)



Precipitation and ITCZ

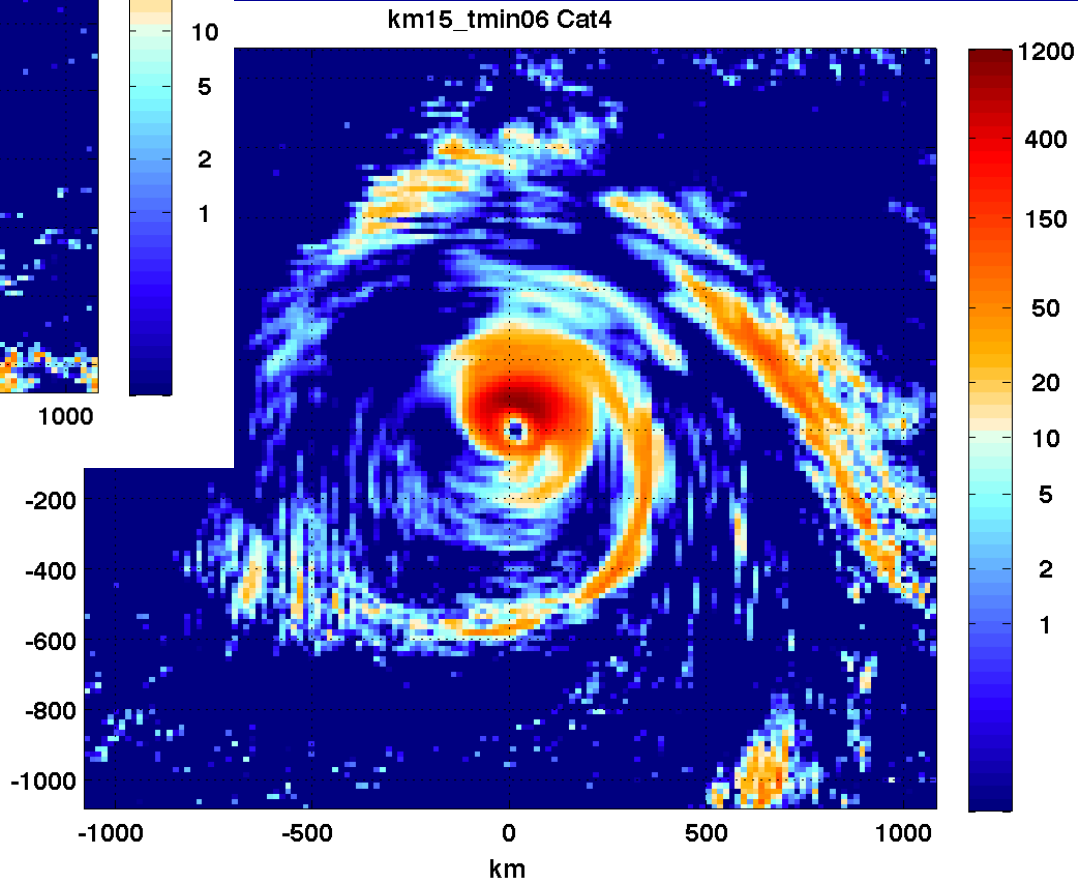


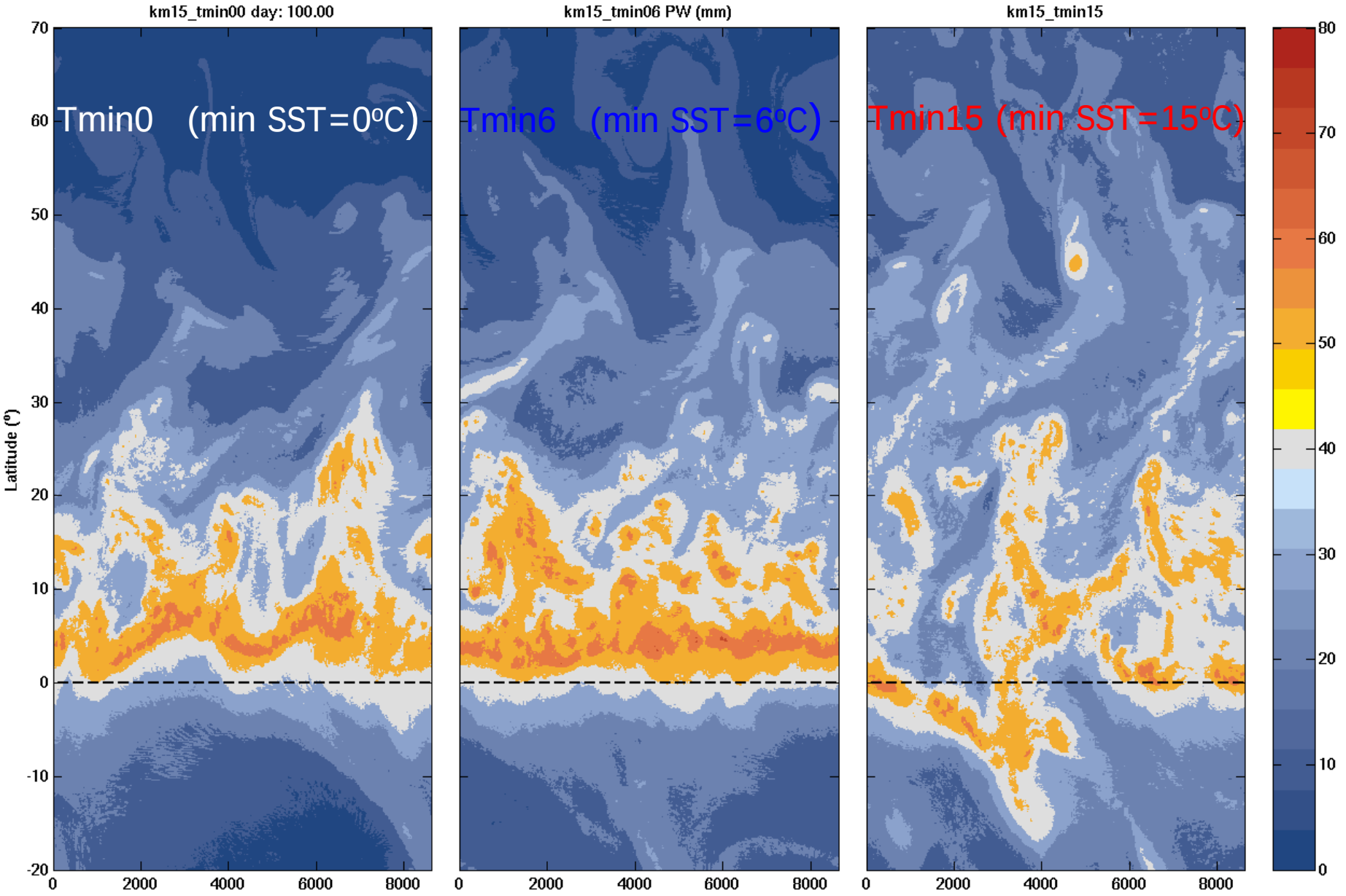
TC examples, Precipitation



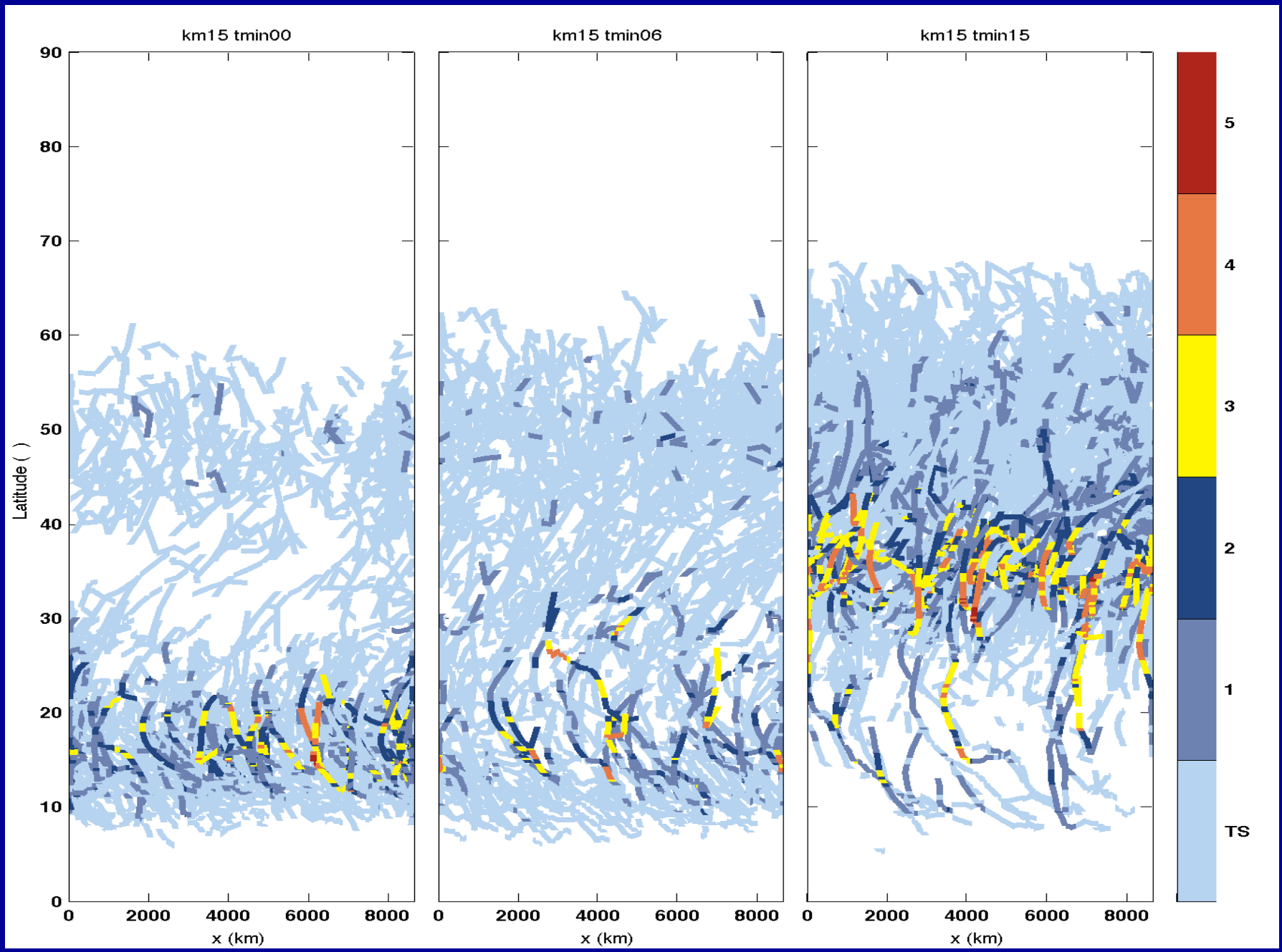
Category 2

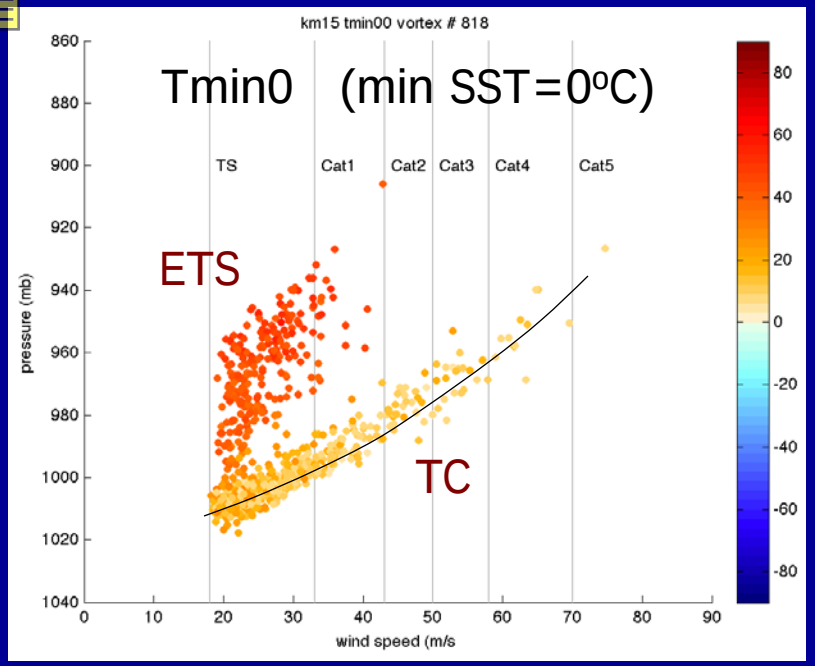
Category 4

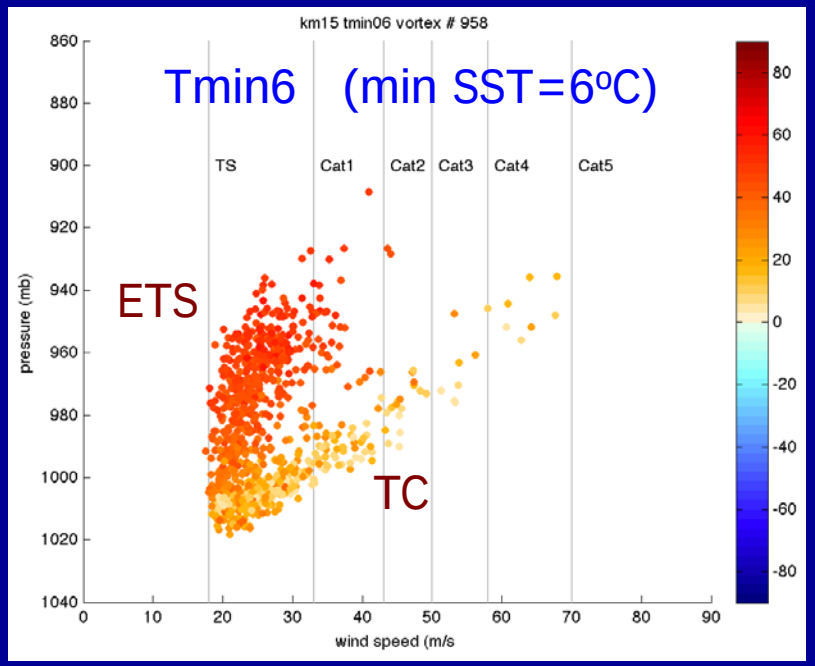


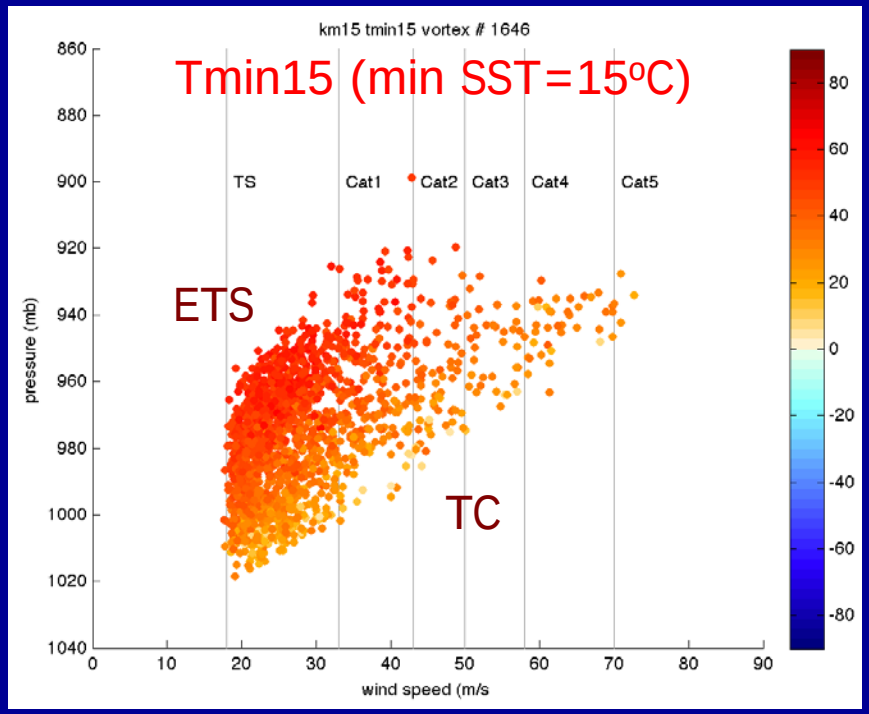

km15_tmin00 day: 100.00
km15_tmin06 PW (mm)
km15_tmin15
Tmin0 (min SST=0ºC)
Tmin6 (min SST=6ºC)
Tmin15 (min SST=15ºC)
Latitude (º)
70
60
50
40
30
20
10
0
-10
-20
0
2000
4000
6000
8000
80
70
60
50
40
30
20
10
0

Tracks of tropical and strong extra-tropical storms





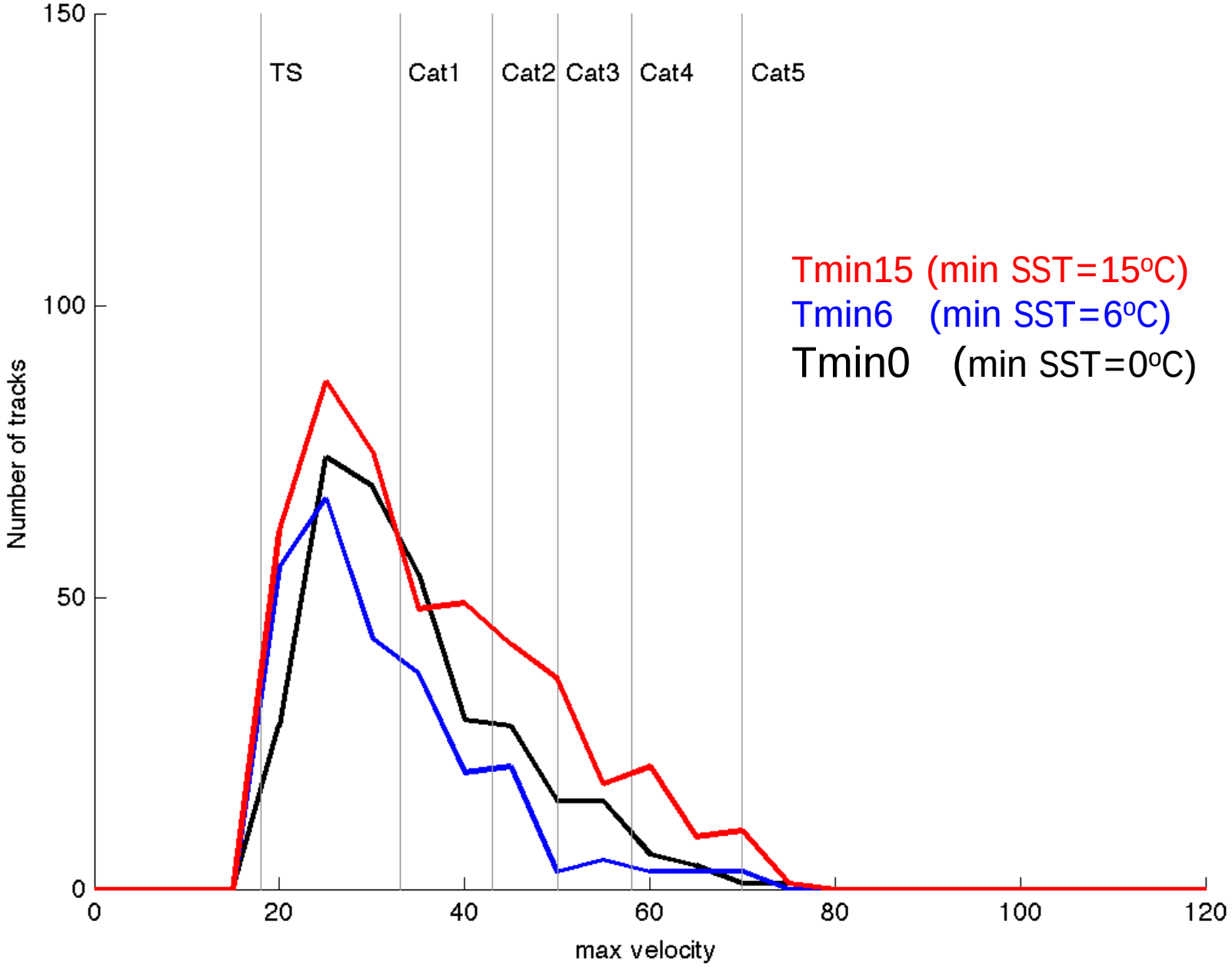




Scatterplots: pressure vs wind-speed

Vort>7.5x10^{-4}
All tracks

Number of storm by strength



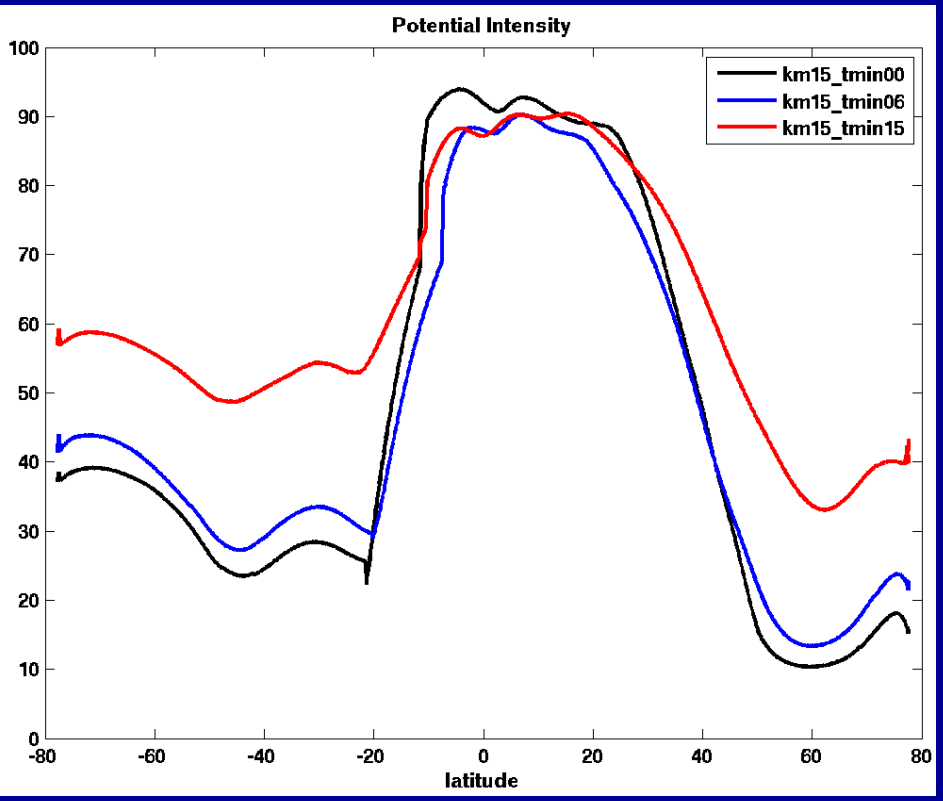
Summary

- Earth's climate is now significantly cooler than the early Pliocene – the last epoch with CO_2 near 400ppm. The difference is as high as 8-10^{o}C in mid to high latitudes over the ocean, and almost 20^{o}C inland in the Arctic.

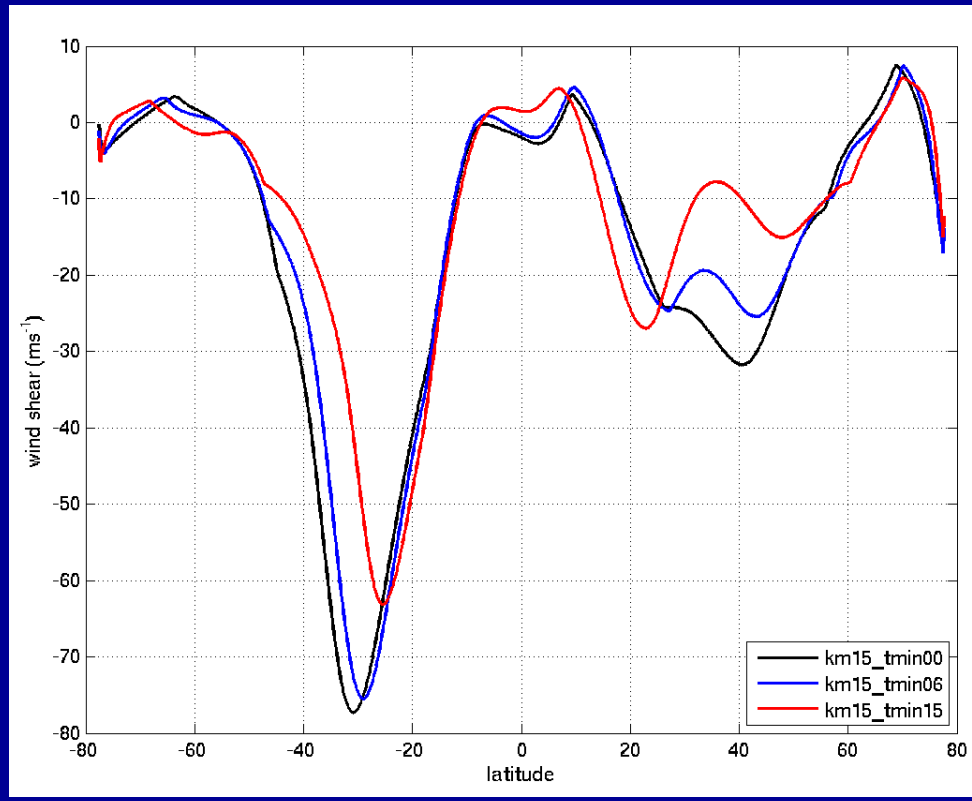
- Whether the climate could return to that of the early Pliocene is unclear. A likely key factor is underestimated cloud feedbacks. If so, we could be severely underestimating the future effects of CO_2 rise (e.g. temperature increase, sea level rise, hurricanes, etc.).

- Tropical cyclone activity changes non-monotonically with reductions in the meridional SST gradient (first decreases then strongly increases)

Potential intensity

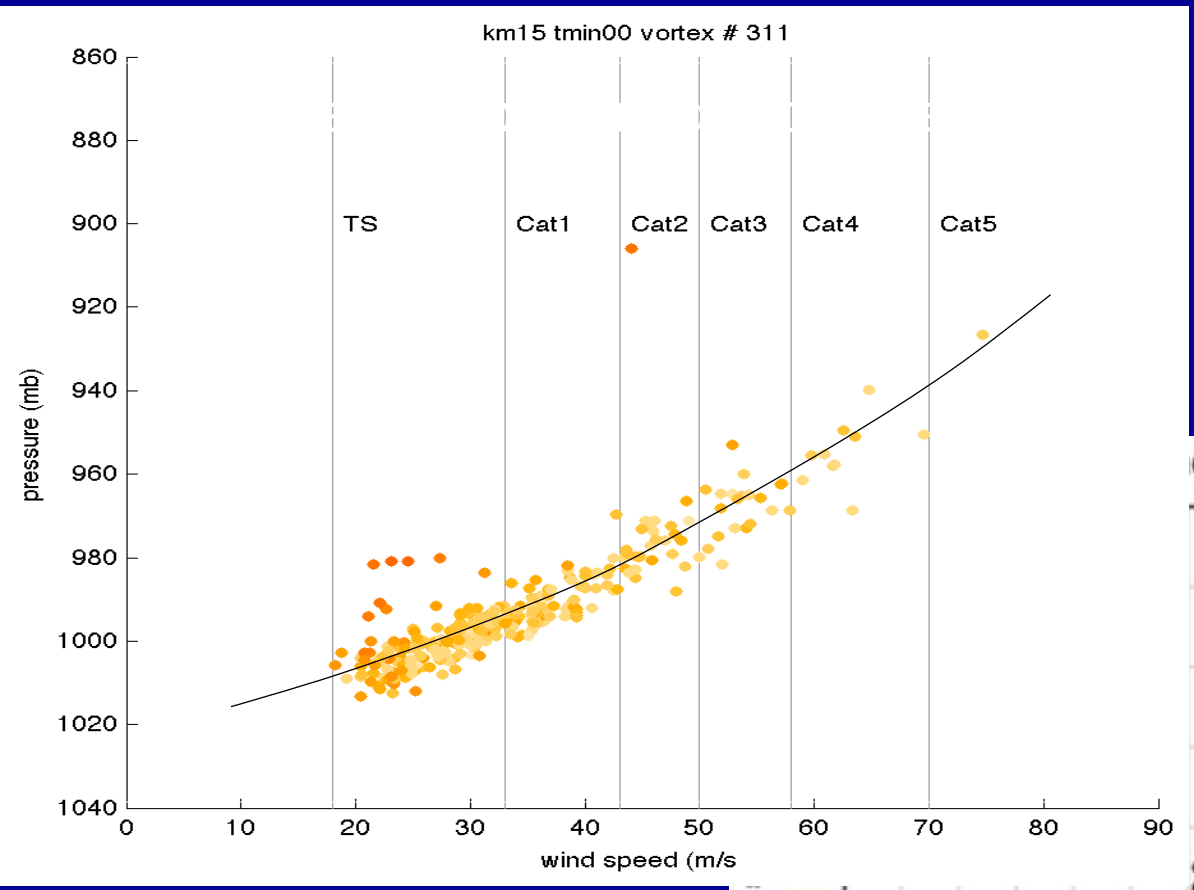


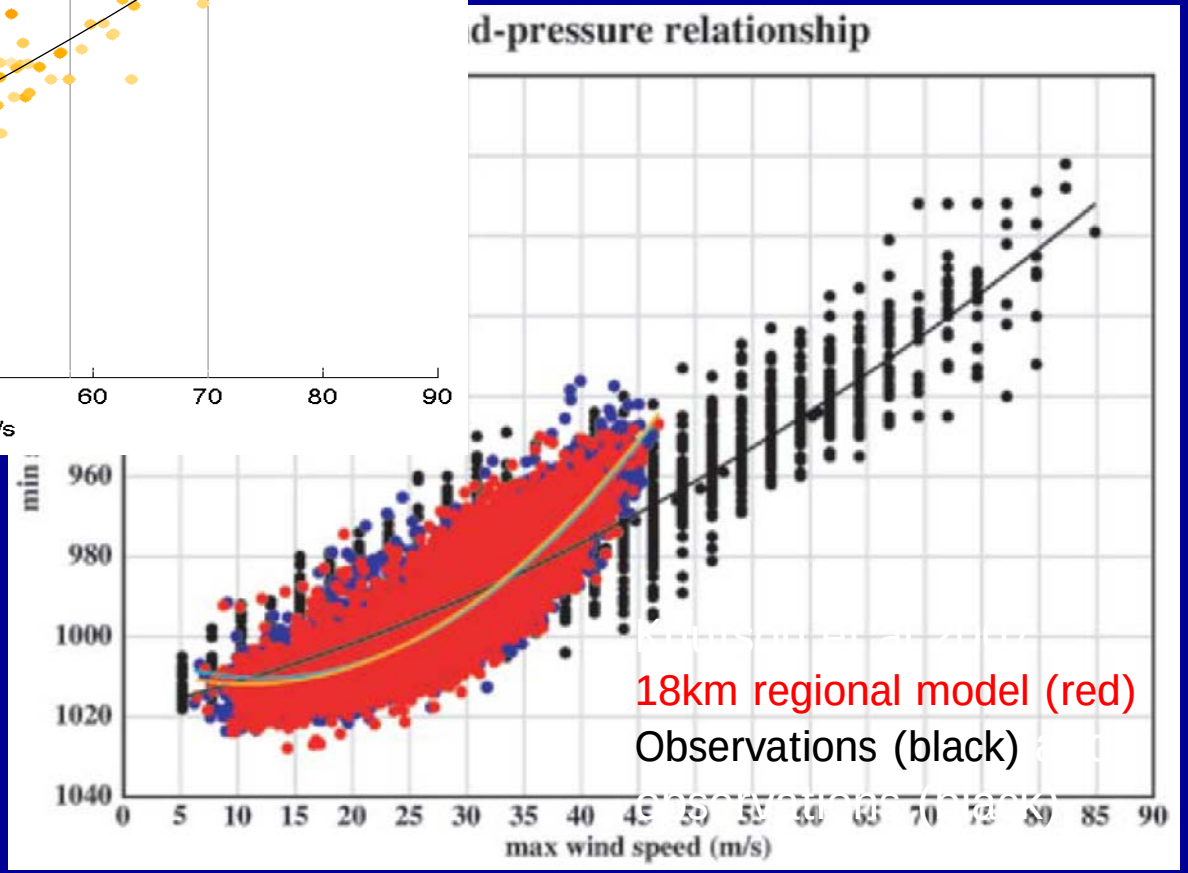
Wind shear



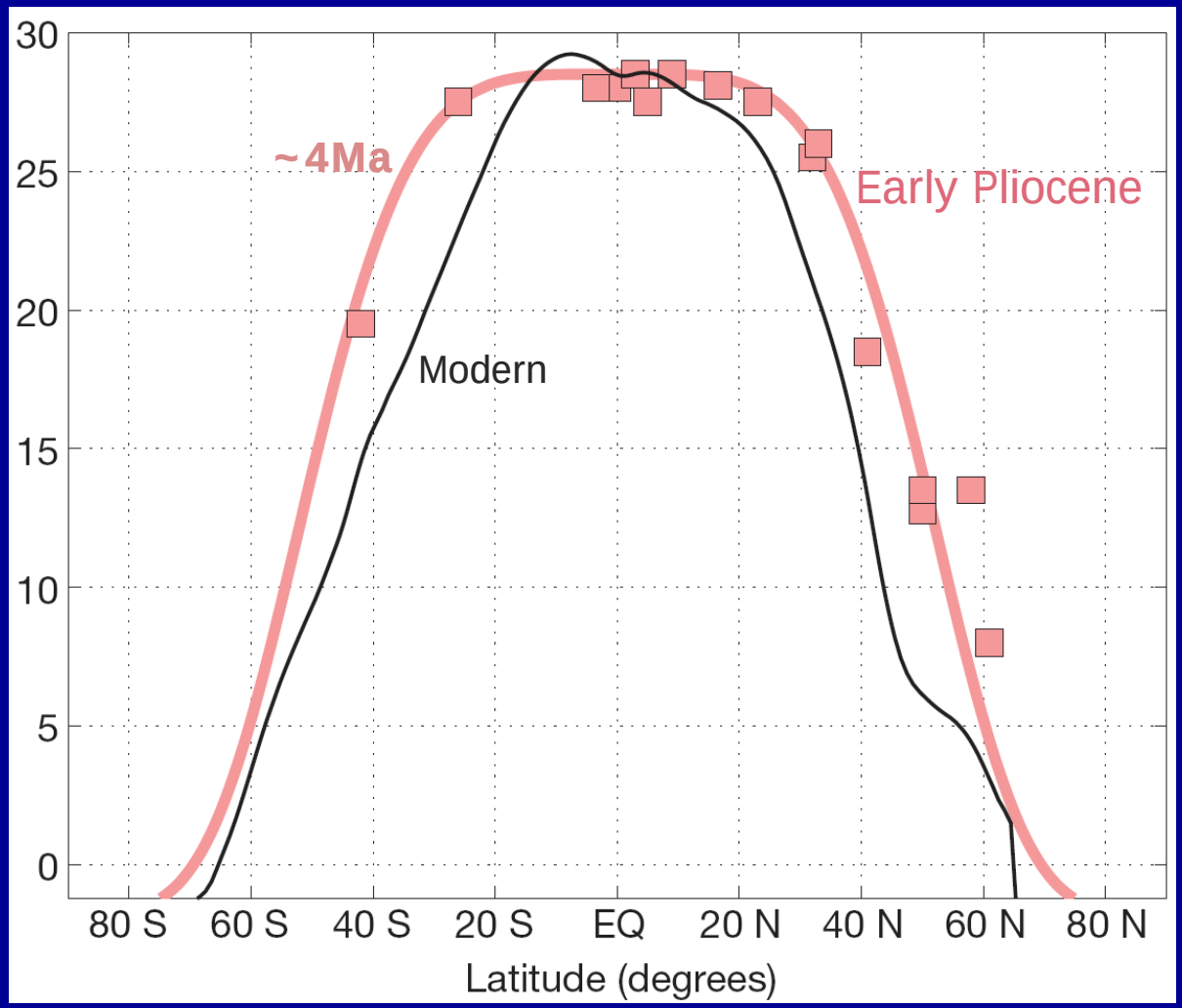
Tmin15 (min SST=15°C)
Tmin6 (min SST=6°C)
Tmin0 (min SST=0°C)

Scatterplots pressure vs wind-speed





Early Pliocene reconstruction and modern sea surface temperatures in the Pacific, ^{o}C



Data:
Alkenones;
Mg/Ca;

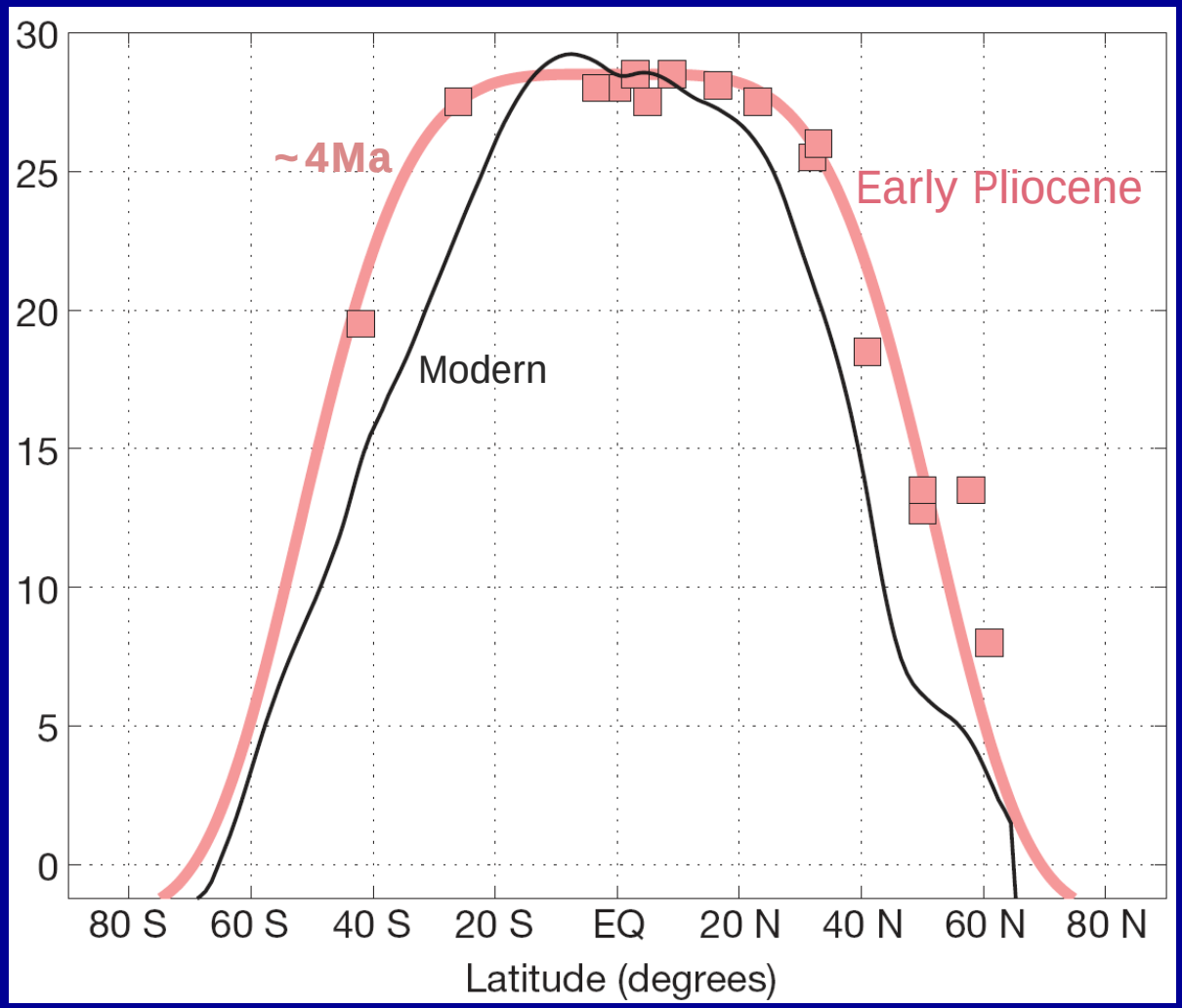
Pacific,
Indian,
and
Atlantic
oceans

Brierley, Fedorov, Liu, Herbert, Lawrence, LaRiviere 2009

Conclusions:

- Using a cloud system resolving model with a 15km resolution and RAVE=15 we are able to simulate realistically the distribution of tropical cyclones including category 5
- TC activity changes non-monotonically with reduction in the meridional SST gradient (first decreases then increases)
- There is a dramatic increase in TC activity in low-gradient climates (think Eocene, Pliocene) and a merging between extra-tropical and tropical storms

Early Pliocene reconstruction and modern sea surface temperatures in the Pacific, ^{o}C



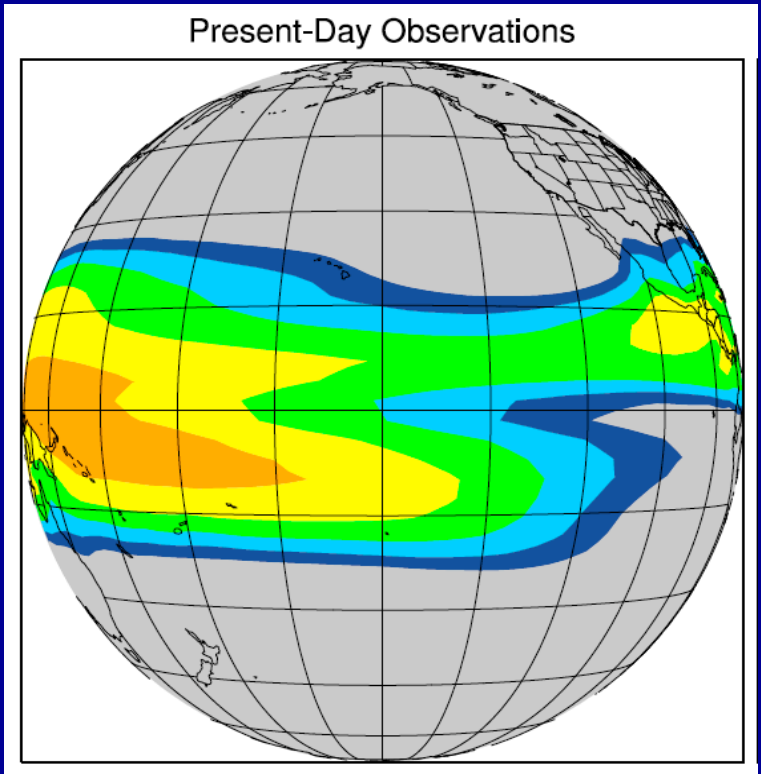
Data:
Alkenones;
Mg/Ca;

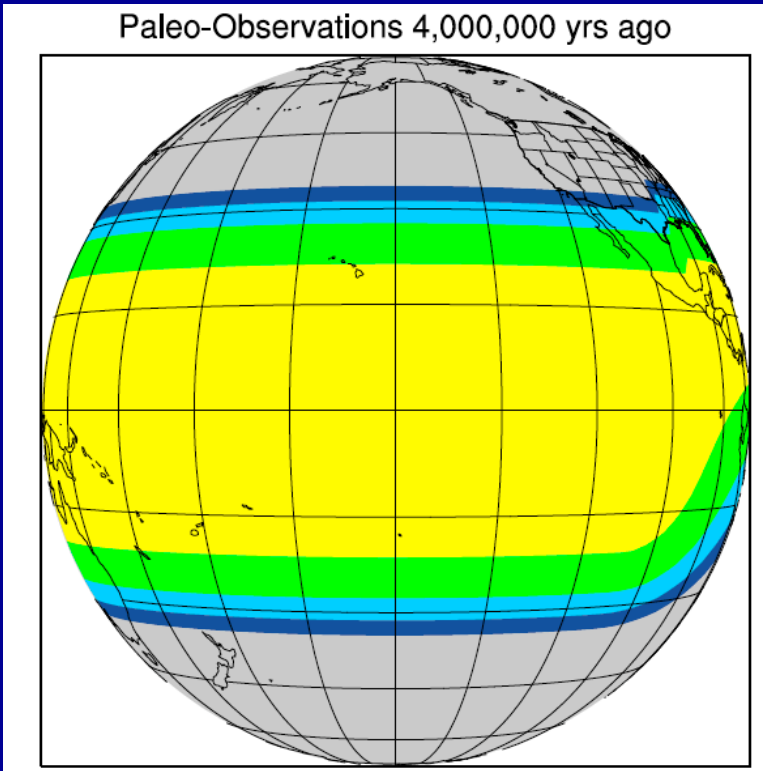
Pacific,
Indian,
and
Atlantic
oceans

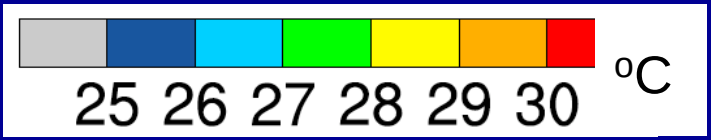
Brierley, Fedorov, Liu, Herbert, Lawrence, LaRiviere 2009

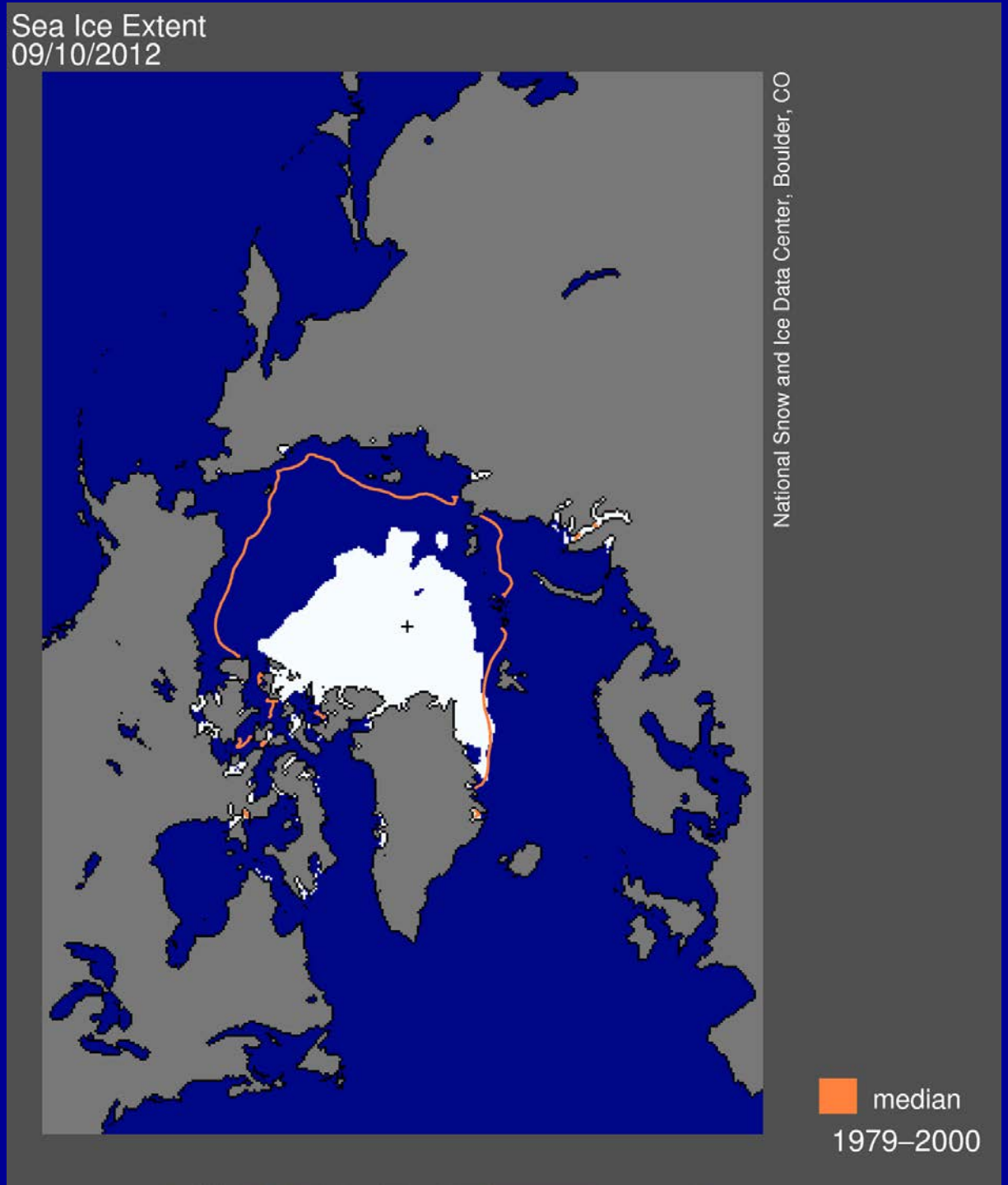
Present-day warm pool

Hypothetical warm pool in the early Pliocene (~4Ma)





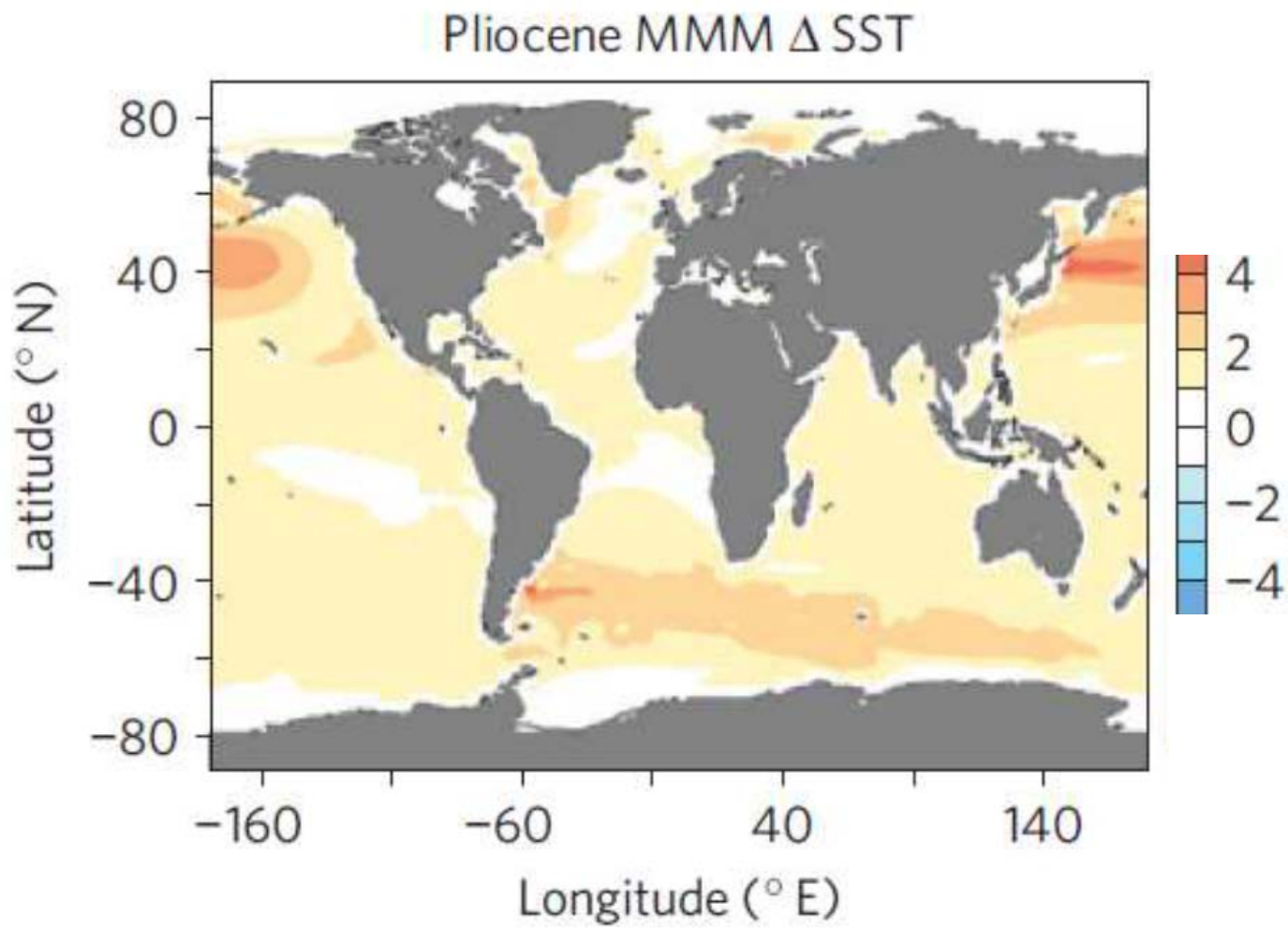


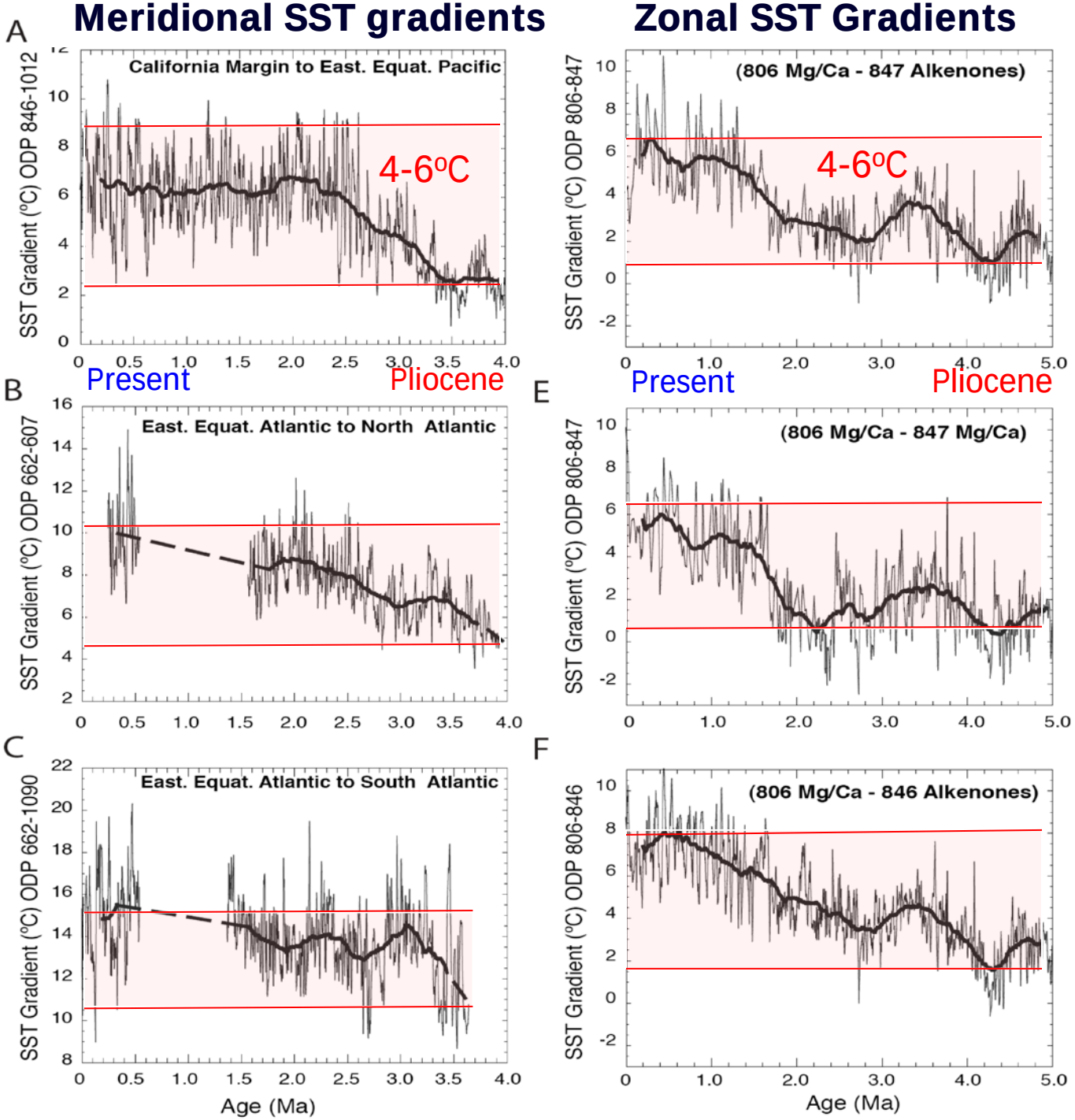


Sea ice extent in September of 2012 versus average ice extent in summer over past 20 years

The area of permanent sea ice is shrinking!

National Snow and Ice Data Center


Pliocene MMM Δ SST
80
40
0
−40
−80
Latitude (° N)
−160
−60
40
140
Longitude (° E)
4
2
0
−2
−4

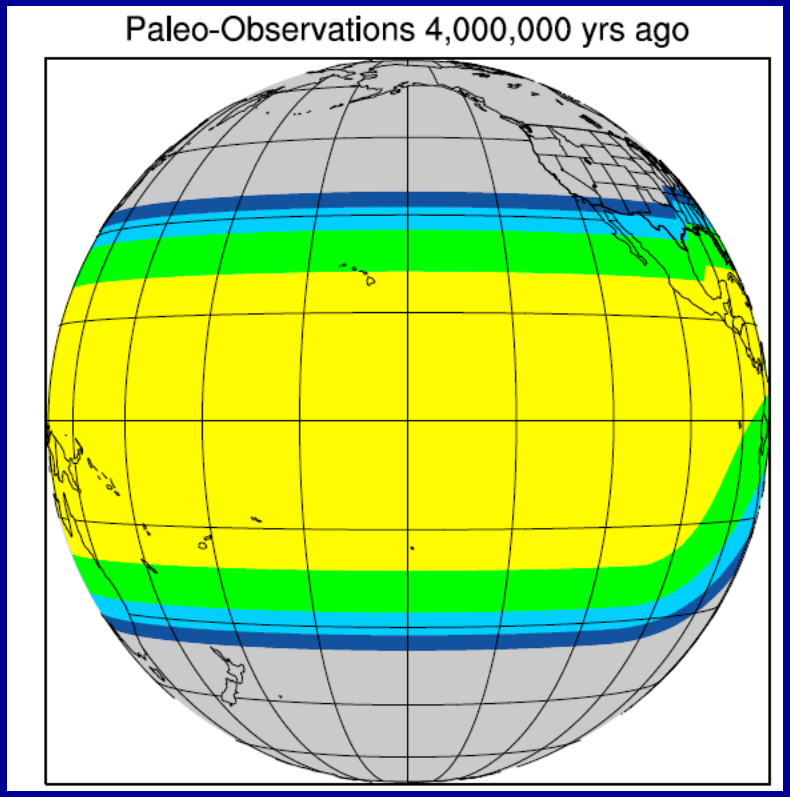


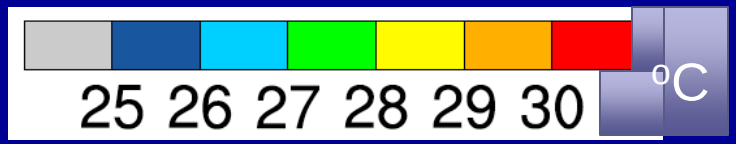
Reduced meridional and zonal SST gradients in the Pliocene!

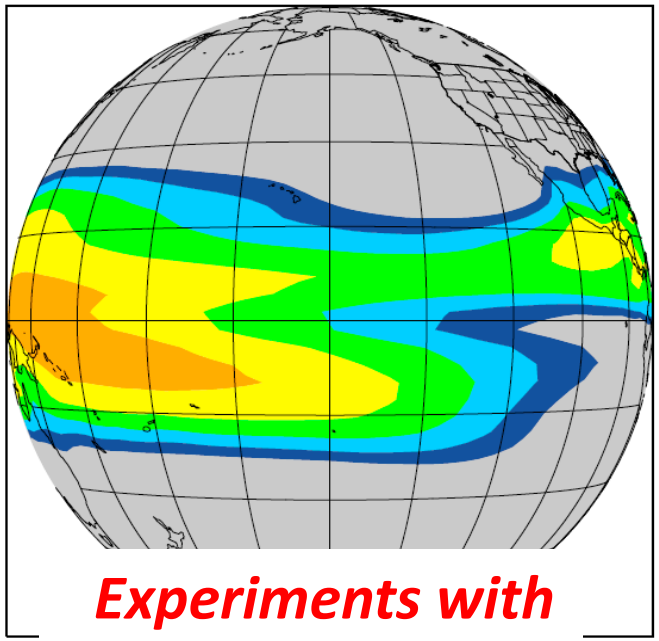
Fedorov, Lawrence, Brierley, Liu, Dekens, Ravelo 2013, Nature

Also:
Martínez-Garcia et al 2010
Dekens et al 2008
Fedorov et al 2006
Wara et al 2005

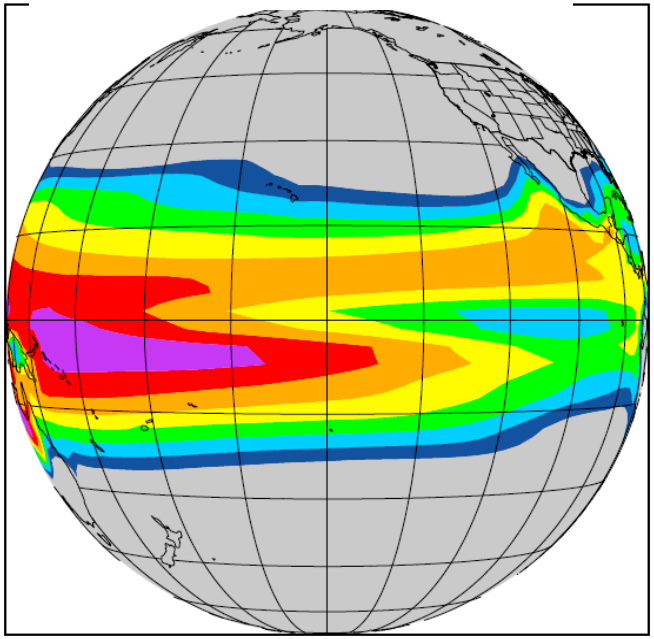
Hypothetical warm pool in the early Pliocene (~4Ma)

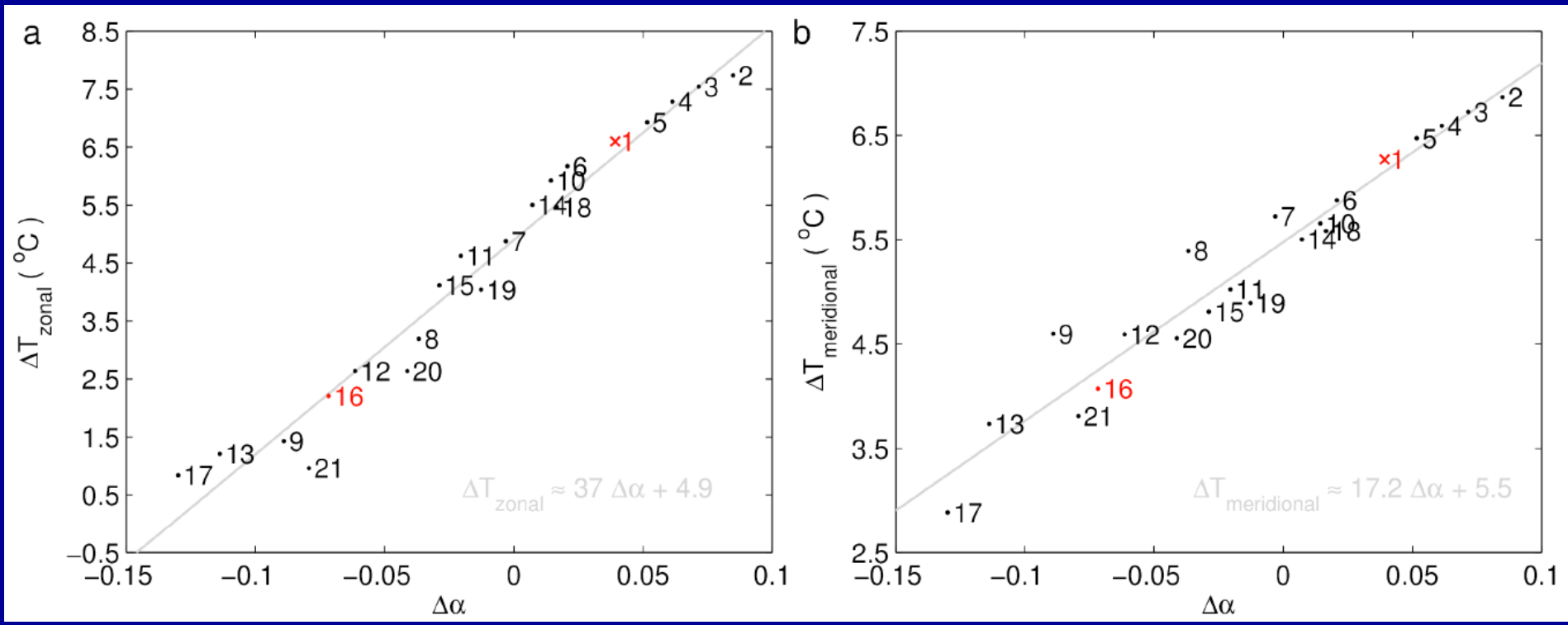




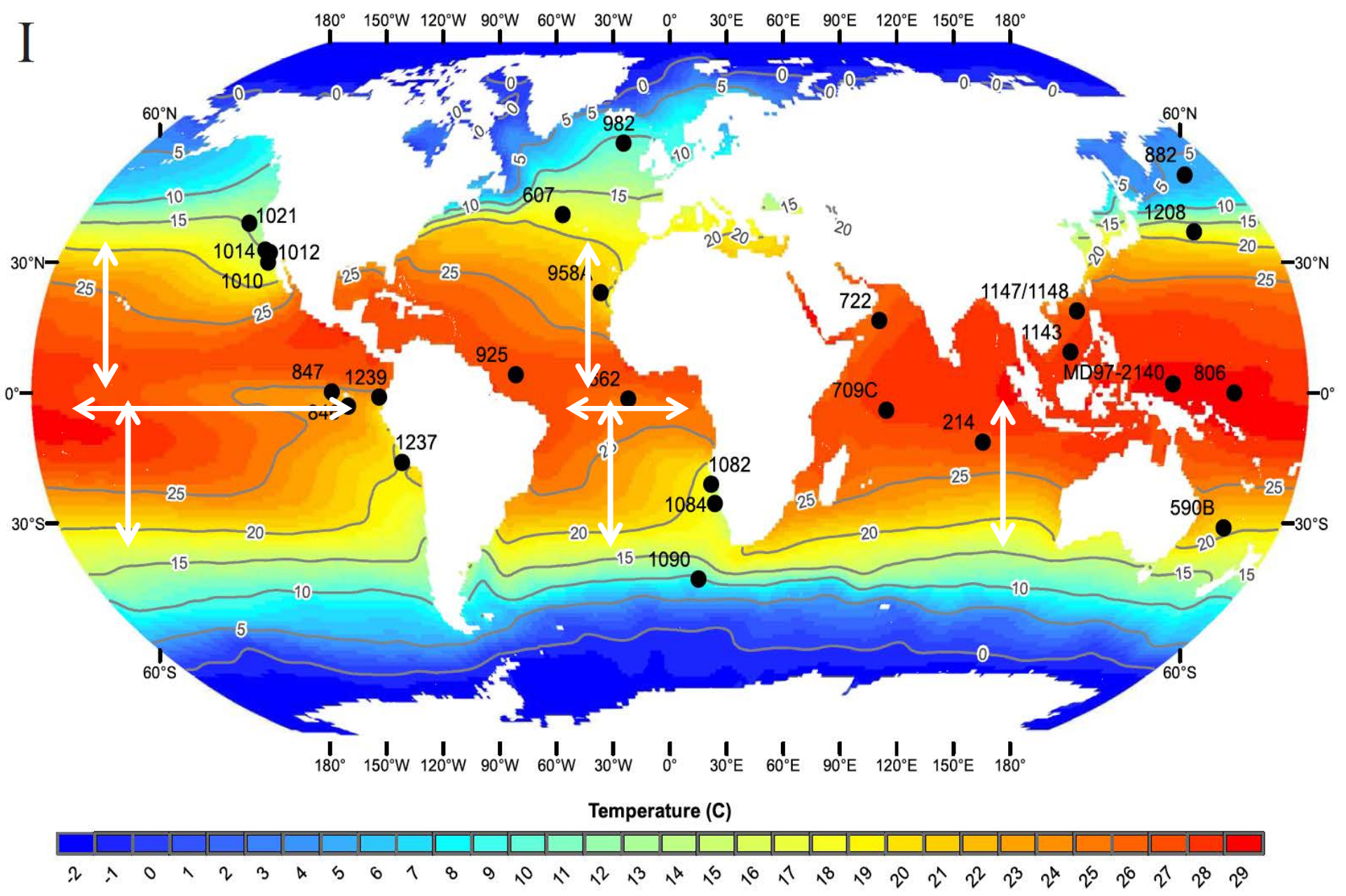


Experiments with coupled GCMs



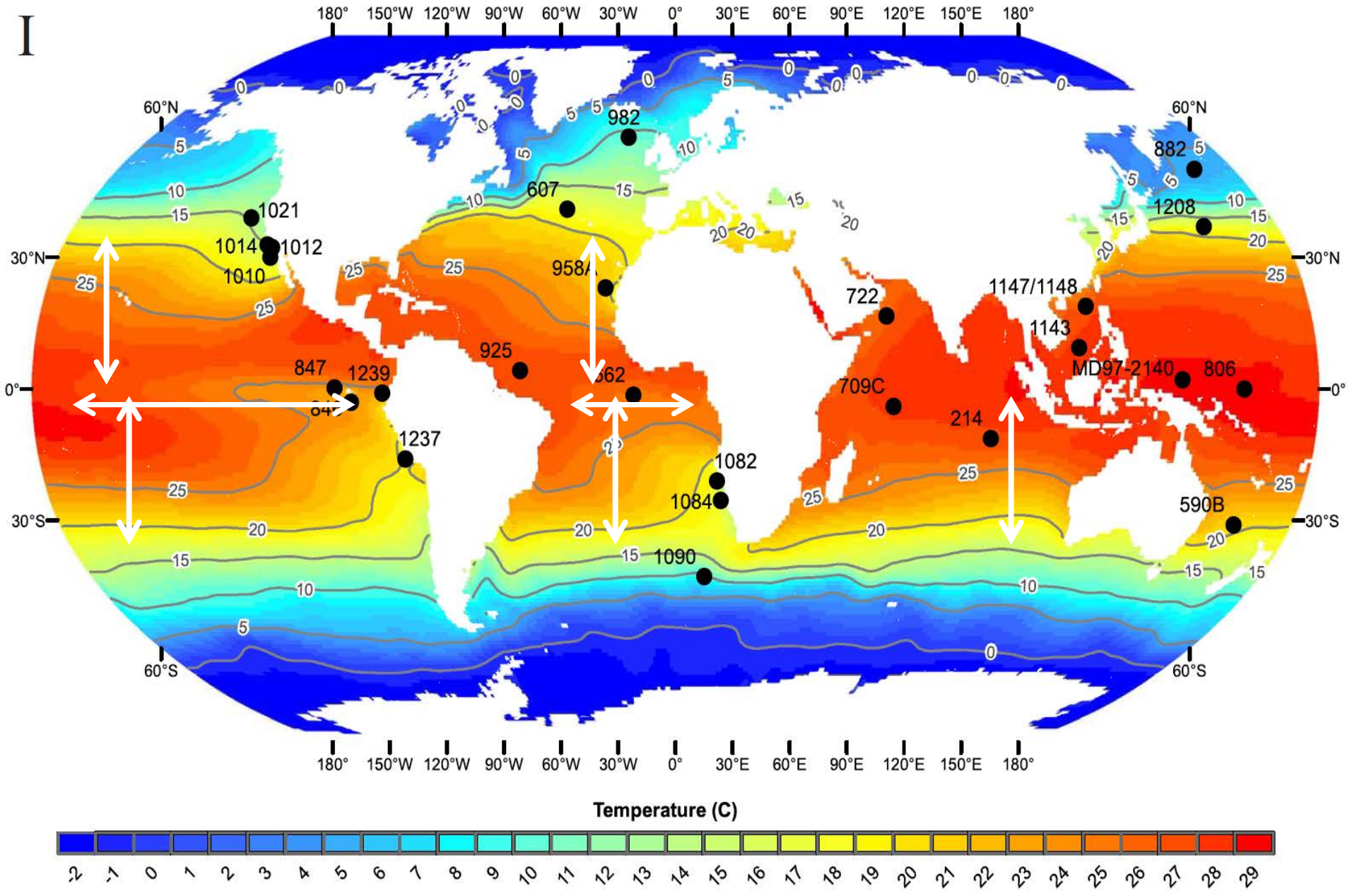

a
b
ΔT zonal (°C)
ΔT meridional (°C)
Δα
ΔT zonal ≈ 37 Δα + 4.9
ΔT meridional ≈ 17.2 Δα + 5.5
×1
16

Climate evolution of the past 5 million years



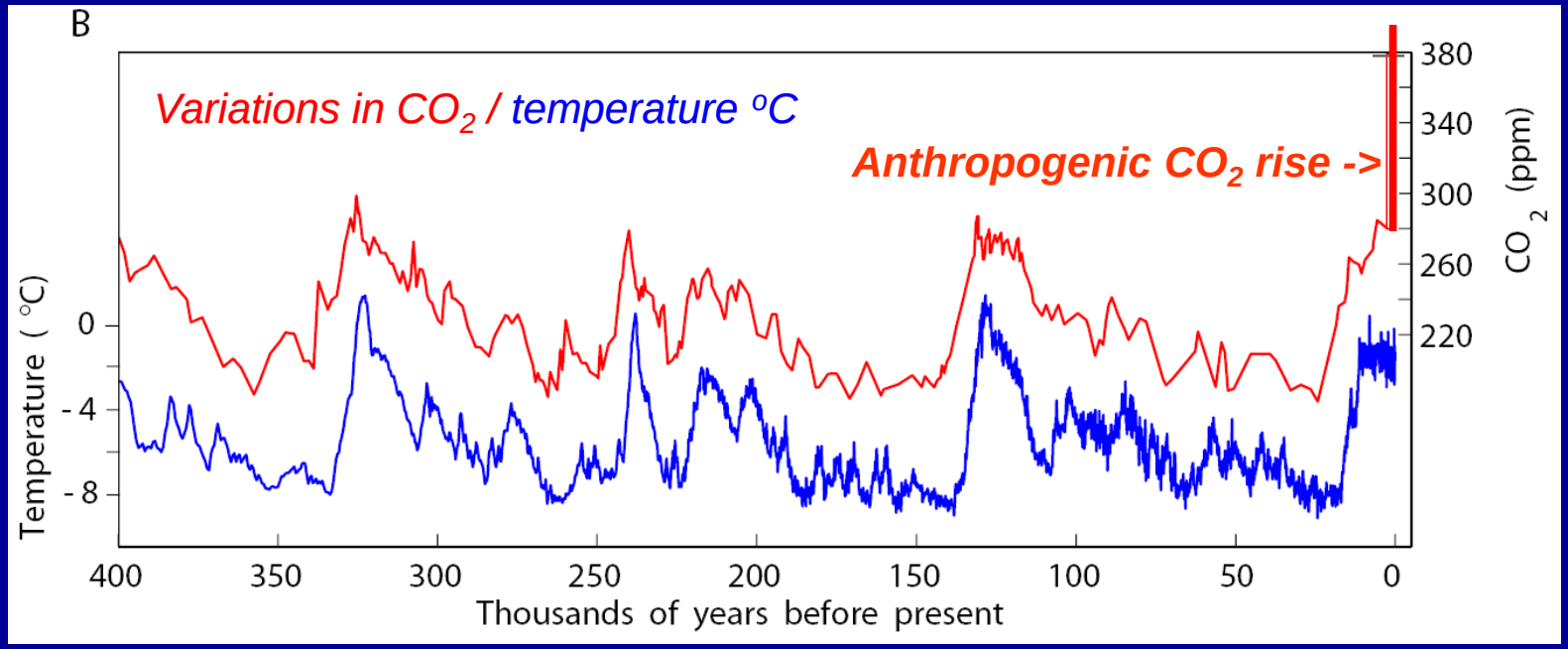
Fedorov, Brierley, Lawrence, Dekens, Liu, Ravelo 2013, Nature

Climate evolution of the past 5 million years



Fedorov, Brierley, Lawrence, Dekens, Liu, Ravelo 2012, Nature, in revision

Variations in CO_2 and proxy temperatures in Antarctica (last 0.5Myr)



***Fedorov et al 2006 in Science**, compiled from Zachos et al 2001 and Petit et al 1999*

Hurricane Statistical DownScaling Model (SDSM)

- *Described in Emanuel 2006*
- *Generates synthetic hurricane tracks*
- *Has a subroutine to calculate hurricane intensity, using an axisymmetric Coupled Hurricane Intensity Prediction System (CHIPS)*
- *Has a simple model for ocean mixing*
- *Takes into account large-scale atmospheric fields (sea surface temperature, lapse rates, specific humidity, wind shear), which can be computed from a large-scale atmospheric GCM*
- *Hurricanes are initiated by random seeding (inserting weak vortices)*

Hurricane Statistical Downscaling Model (SDSM)

- *Described in Emanuel 2006*
- *Generates synthetic hurricane tracks*
- *Has a subroutine to calculate hurricane intensity, using an axisymmetric Coupled Hurricane Intensity Prediction System (CHIPS)*
- *Has a simple model for ocean mixing*
- *Takes into account large-scale atmospheric fields (sea surface temperature, lapse rates, specific humidity, wind shear), which can be computed from a large-scale atmospheric GCM*
- *Hurricanes are initiated by random seeding (inserting weak vortices)*

For example, synthetic hurricane tracks (the hurricane location in time) are obtained by integrating spatial velocity with time :

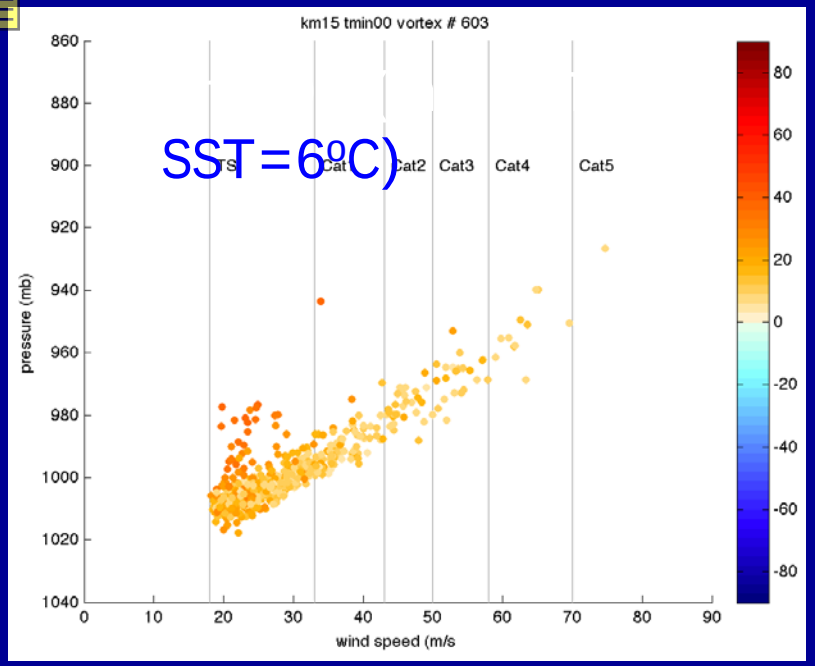
$$\frac{d\mathbf{x}}{dt} = \mathbf{V}_{\text{track}}$$

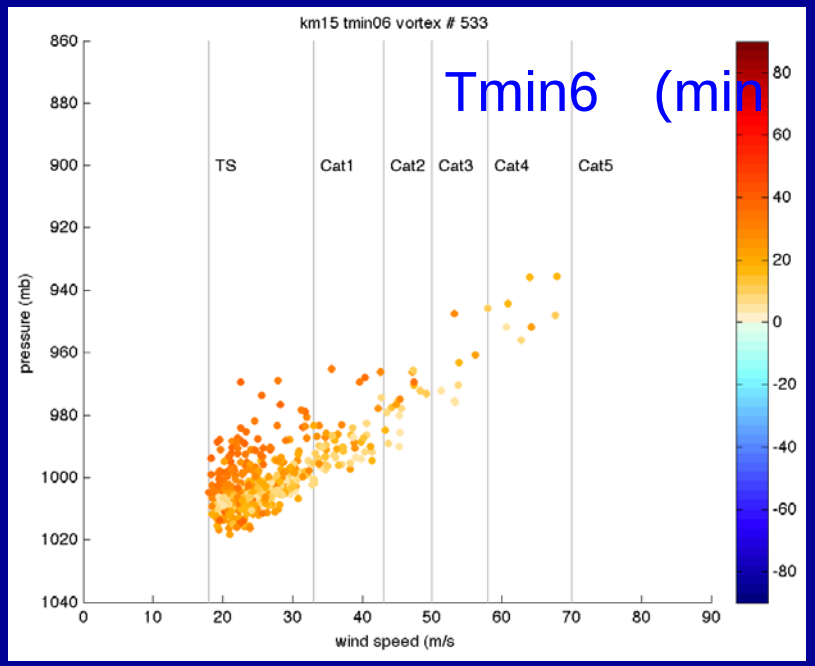
$$\mathbf{V}_{\text{track}} = \alpha\mathbf{V}_{850} + (1-\alpha)\mathbf{V}_{250} + \mathbf{V}_{\beta}$$

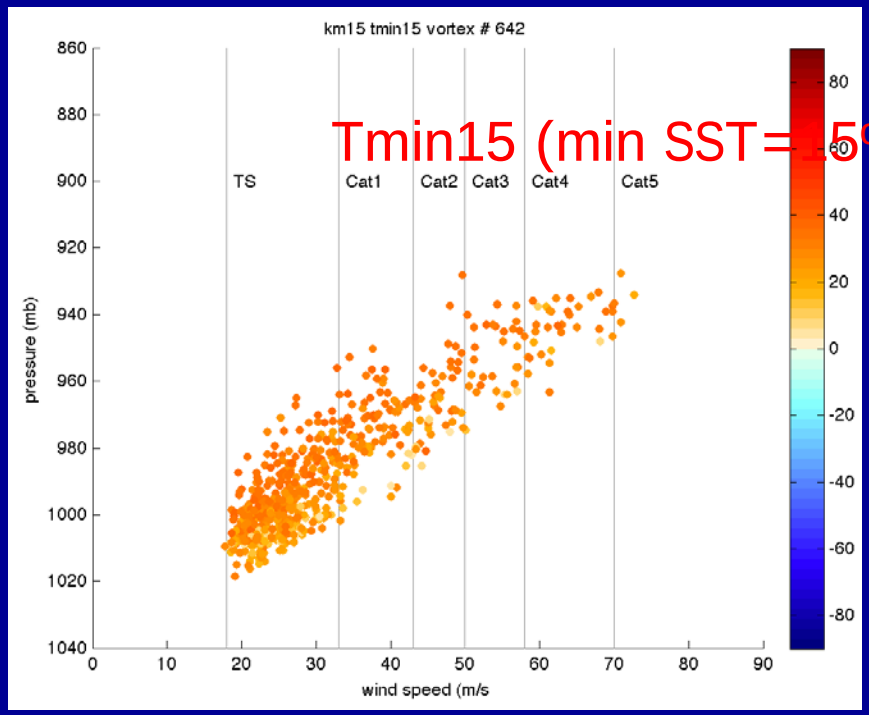
$\mathbf{V}_{850}$ and $\mathbf{V}_{250}$ are flows at two pressure levels (two altitudes)

α- a weighting coefficient

$\mathbf{V}_{\beta}$ – is beta-drift (advection of a vortex due to planetary rotation)

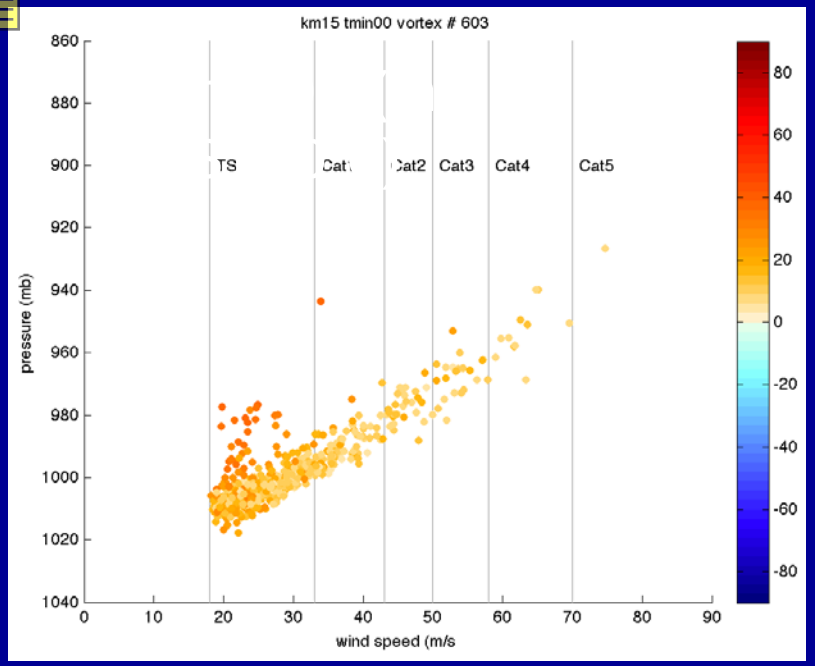






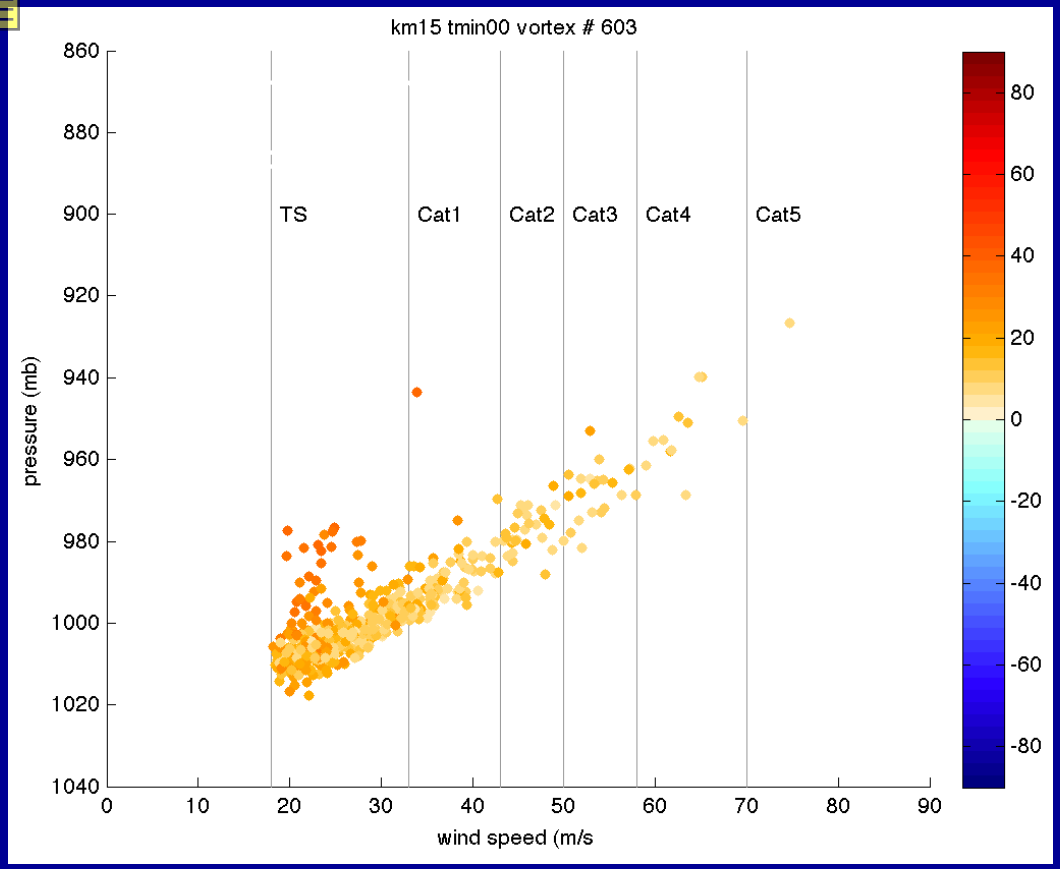
Vort>7.5x10^{-4}
GenLat<40ºN

Scatterplots: pressure vs wind-speed



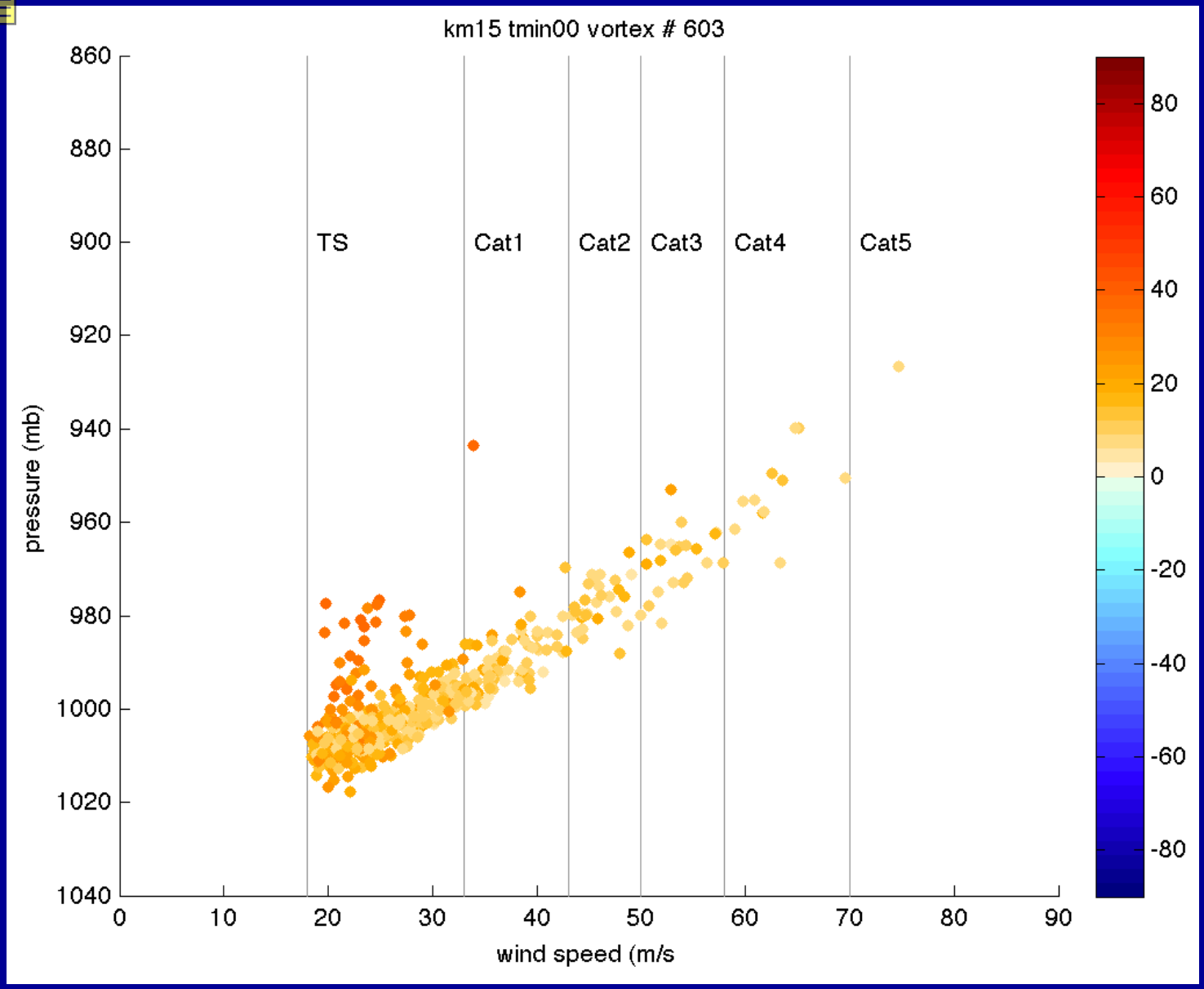
Present-day climate

Vort > 7.5×10^{-4}
GenLat < 40ºN

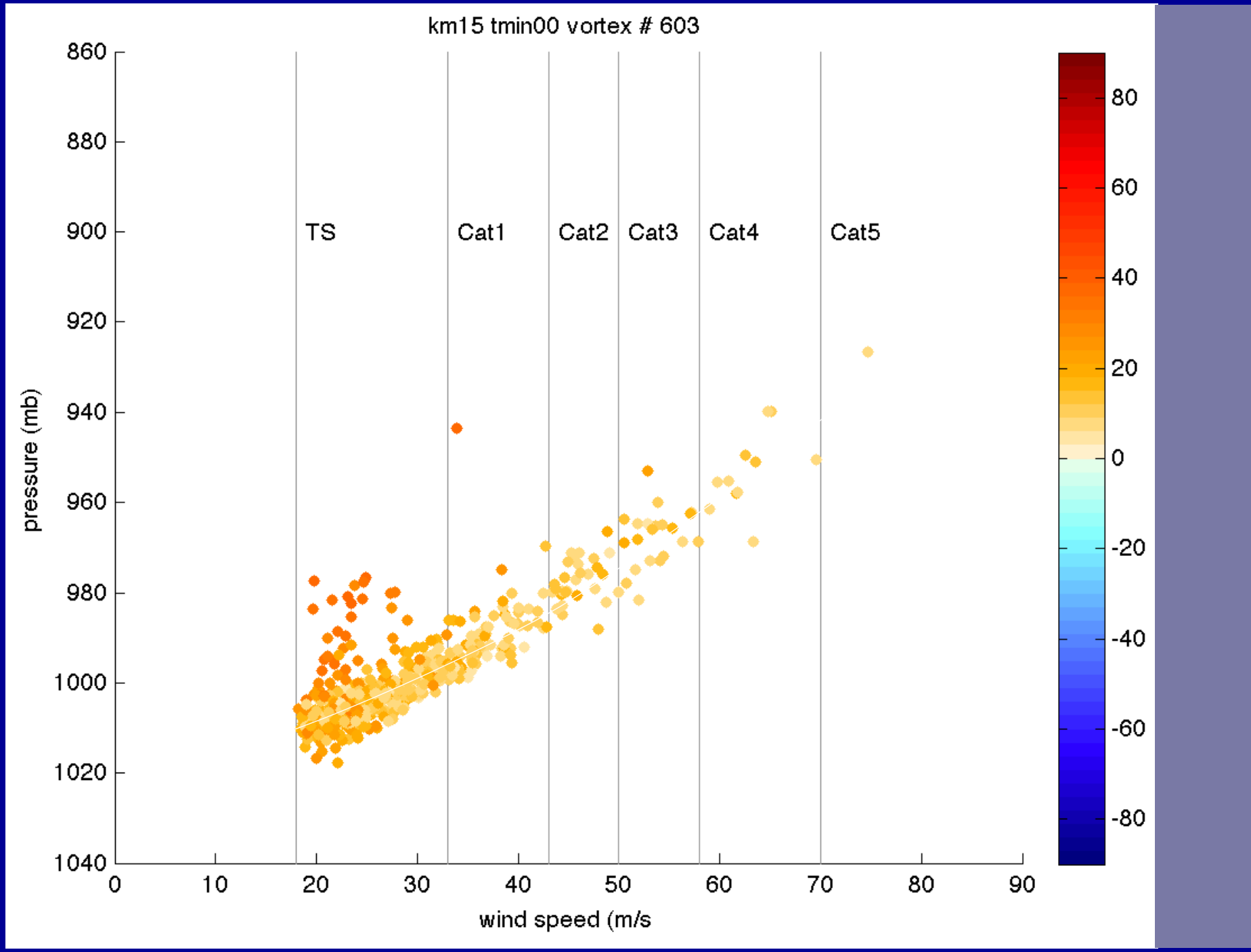


Present-day climate

Vort>7.5x10^{-4}
GenLat<40ºN



Vort>7.5x10^{-4}
GenLat<40ºN


km15 tmin00 vortex # 603
pressure (mb)
wind speed (m/s)
TS
Cat1
Cat2
Cat3
Cat4
Cat5
860
880
900
920
940
960
980
1000
1020
1040
0
10
20
30
40
50
60
70
80
90
80
60
40
20
0
-20
-40
-60
-80

Experimental Set-up:

Model: SAM = System for Atmospheric Modeling

- ✧ Cloud System or Cloud Resolving Model, Khairoutdinov and Randall 2003
- ✧ Convection is simulated directly (not parameterized)
- ✧ Aqua-planet, equatorial β-plane, 1/4 of the globe, periodic b.c.
- ✧ Resolution: 15km

$$\gamma^2 \frac{Dw}{Dt} = -\frac{\partial p'}{\rho \partial z} + B$$

- ✧ RAVE (Reduced Acceleration in the Vertical), Kuang et al 2005

Hypothetical warm pool in the early Pliocene (~4Ma)