Tropical cyclones in a warming world

A climate model perspective

Julien Cattiaux[1,2]

+ Olivier Bousquet[2], Fabrice Chauvin[1], Sylvie Malardel[2] & Chia-Lun Tsai[2]

1. Centre National de Recherches Météorologiques, Toulouse, France.
2. Laboratoire de l'Atmosphère et des Cyclones, Saint-Denis, La Réunion, France.

julien.cattiaux@meteo.fr | @julienc4ttiaux

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Climate change

Tropical cyclones in climate models

Tropical cyclones and climate change

ARPEGE experiments

Climate models

Components:

atmosphere, ocean, land surface, sea ice, ice sheets, etc. + coupling
+ modules (carbone cycle, aerosols, vegetation, atmospheric chemistry, etc.)

Resolution:

500 km in the 1990s, 200 km in the 2000s, 100 km in the 2010s... 50 km now?

Main atm. parameterizations:

turbulence, convection, clouds, gravity waves, etc.

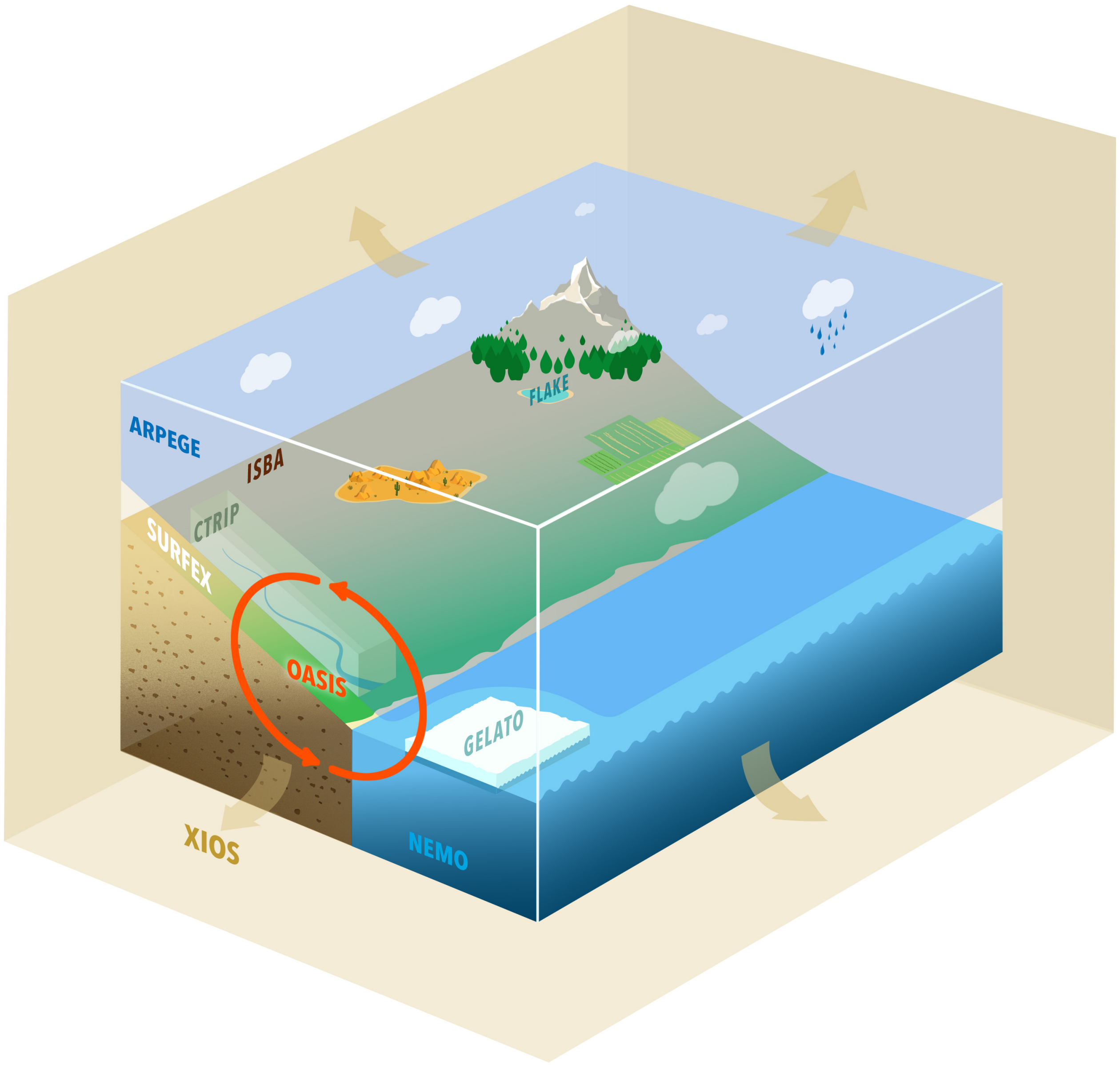
Performance:

typically a dozen of simulated years per day.
1 daily variable 1 level 1 year = $\sim$50 Mo.

International context:

Coupled Model Intercomparison Project: standardized protocols / shared data.
2013 - 5th phase (CMIP5) = 25 centers, 60 versions of models.
2019 - 6th phase (CMIP6) = more?

CNRM climate model



CNRM-CM

Atmosphere:

ARPEGE 6.3
T127 ($\sim$150 km)
+ T359 (some exps)
91 levels

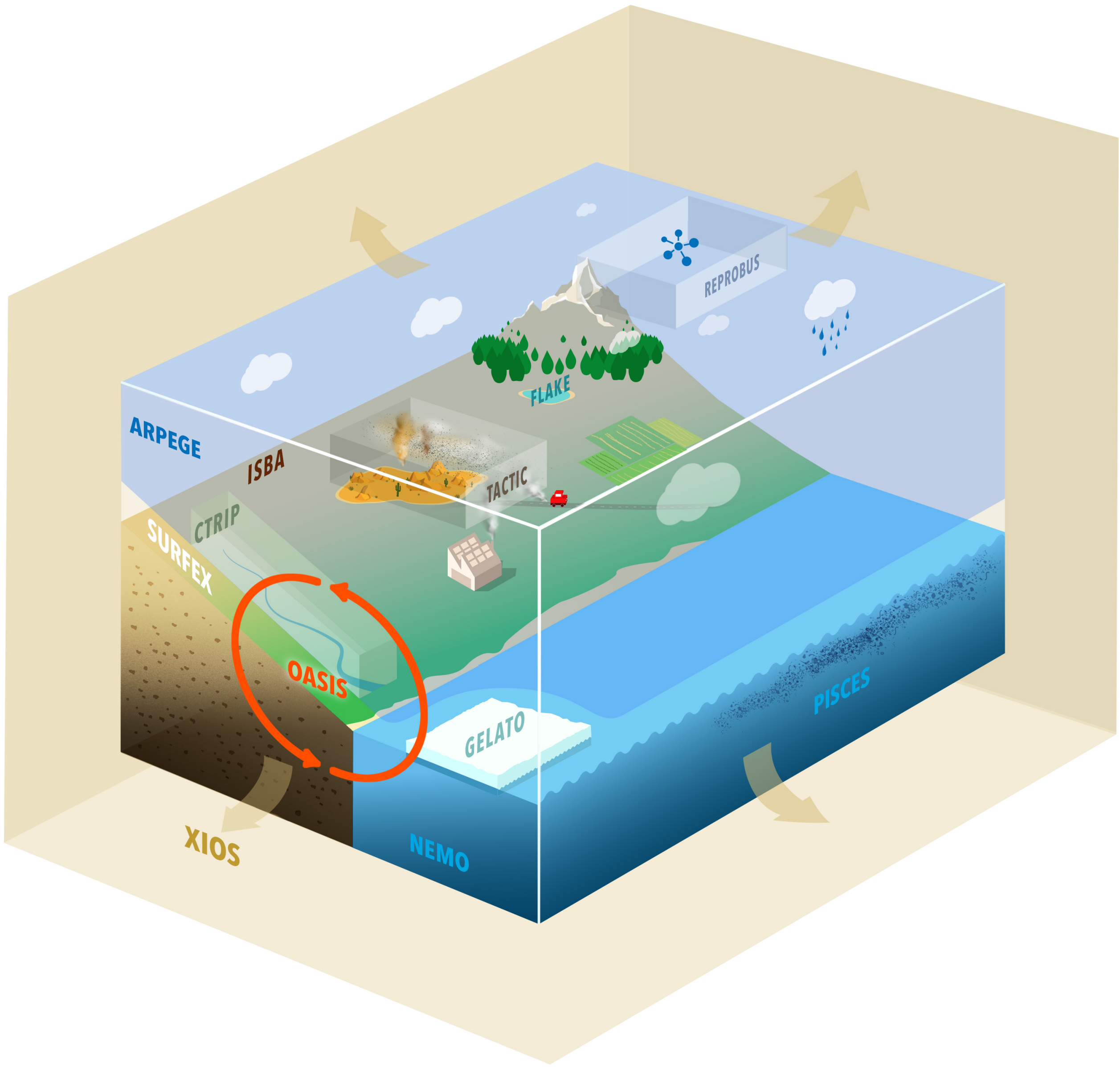
Ocean:

NEMO 3.6
1°/ 75 levels
(1/3°in the tropics)

Surface:

SURFEX 8
ISBA-CTRIP

CNRM climate model



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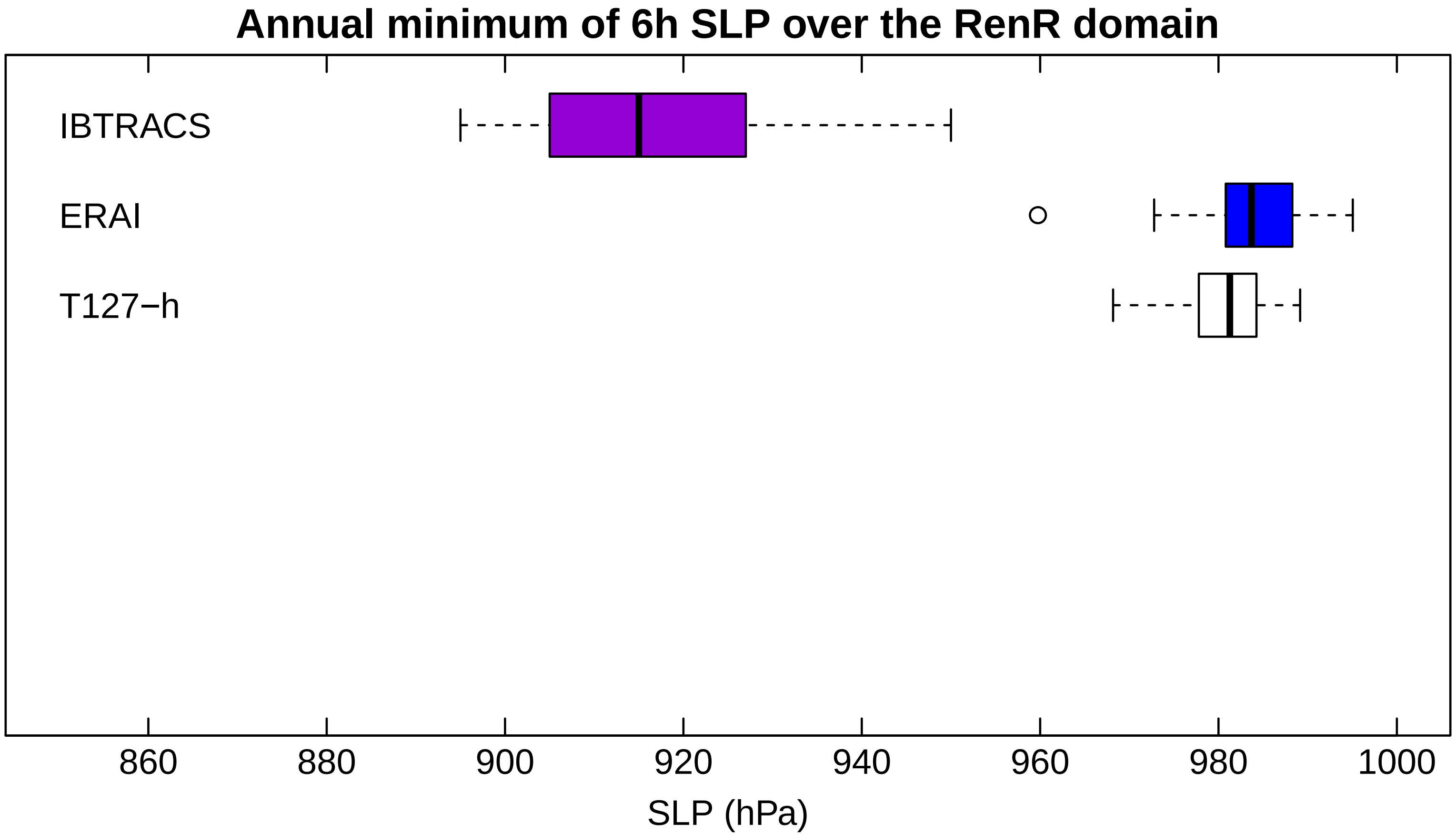
ISBA-CTRIP

How low can we go?

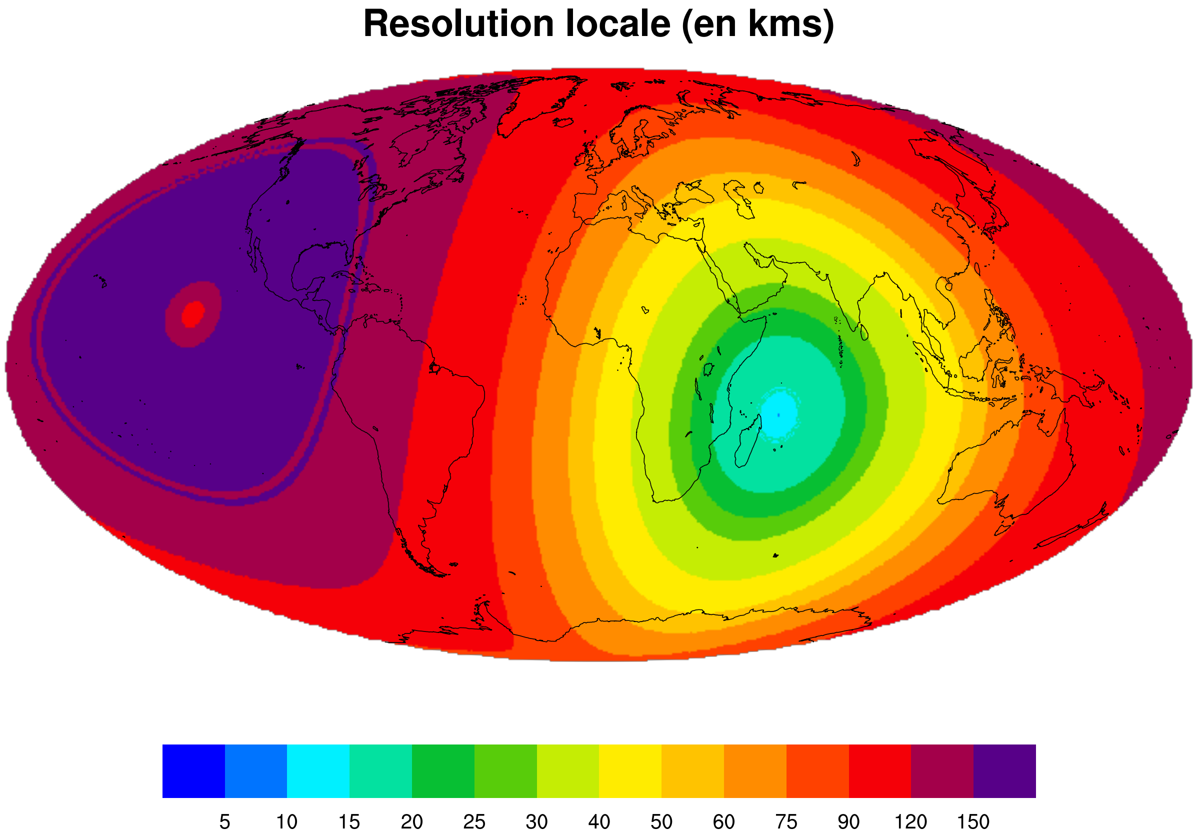
- Distribution of the annual minimum of sea-level pressure over the Southern Indian Ocean (domain 30–120 °W, 0–30 °S).



Reference: IBTRACS (1979–2017). Median = 915 hPa.
Reanalysis: ERAI (1979–2017, 80 km).
Model: CNRM-CM T127 (150 km).

Option A: higher resolution

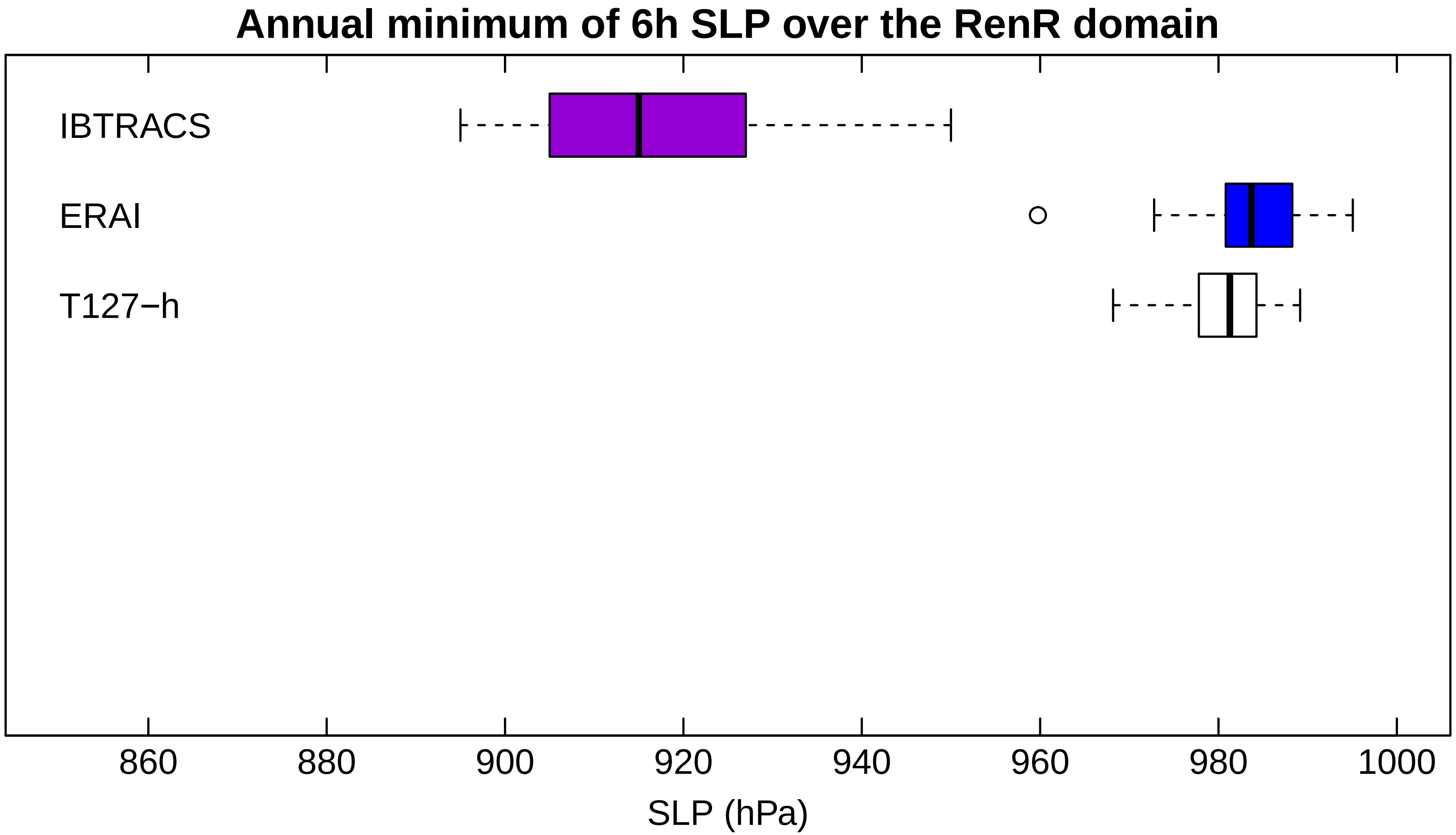
- (Only) a few modeling centers can afford higher-resolution simulations on long time periods.
- At CNRM, a few CMIP6 experiments will be provided with resolution T359 + a stretched configuration of ARPEGE has been developed for long.



Example of the stretched T359 grid used for RenovRisk simulations, © F. Chauvin.

How low can we go? (cont.)

- Distribution of the annual minimum of sea-level pressure over the Southern Indian Ocean (domain 30–120 °W, 0–30°S).



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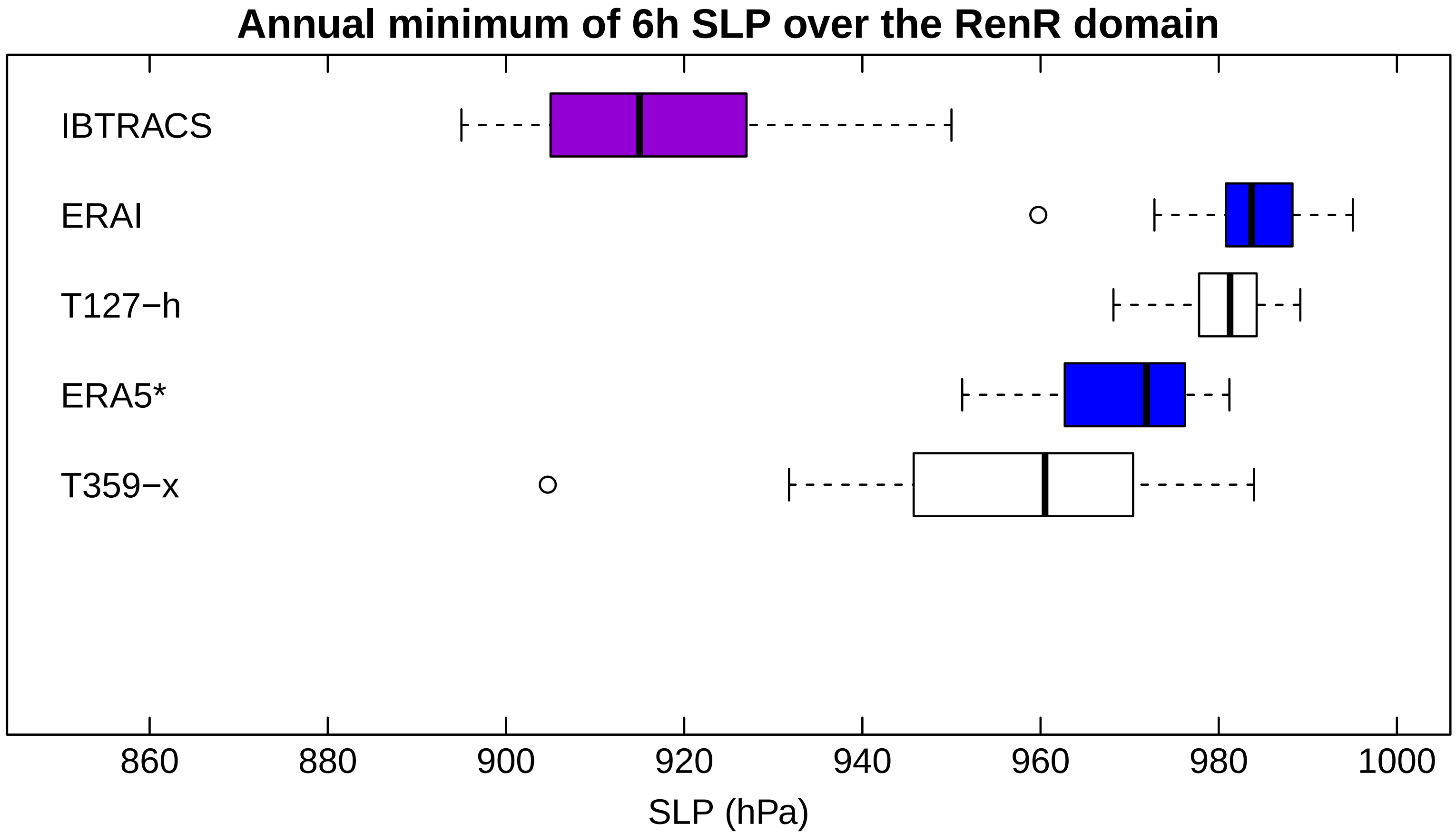

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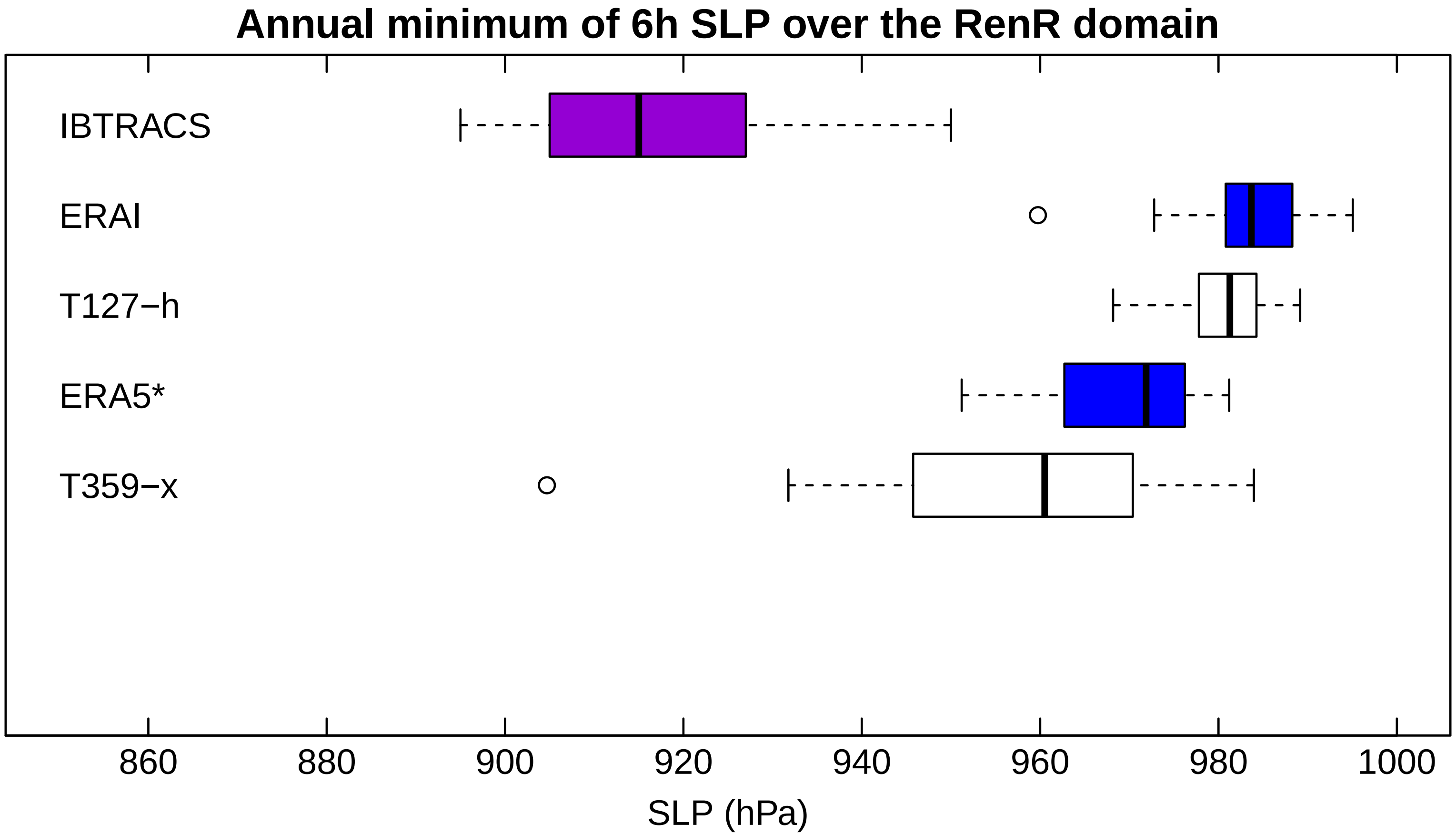

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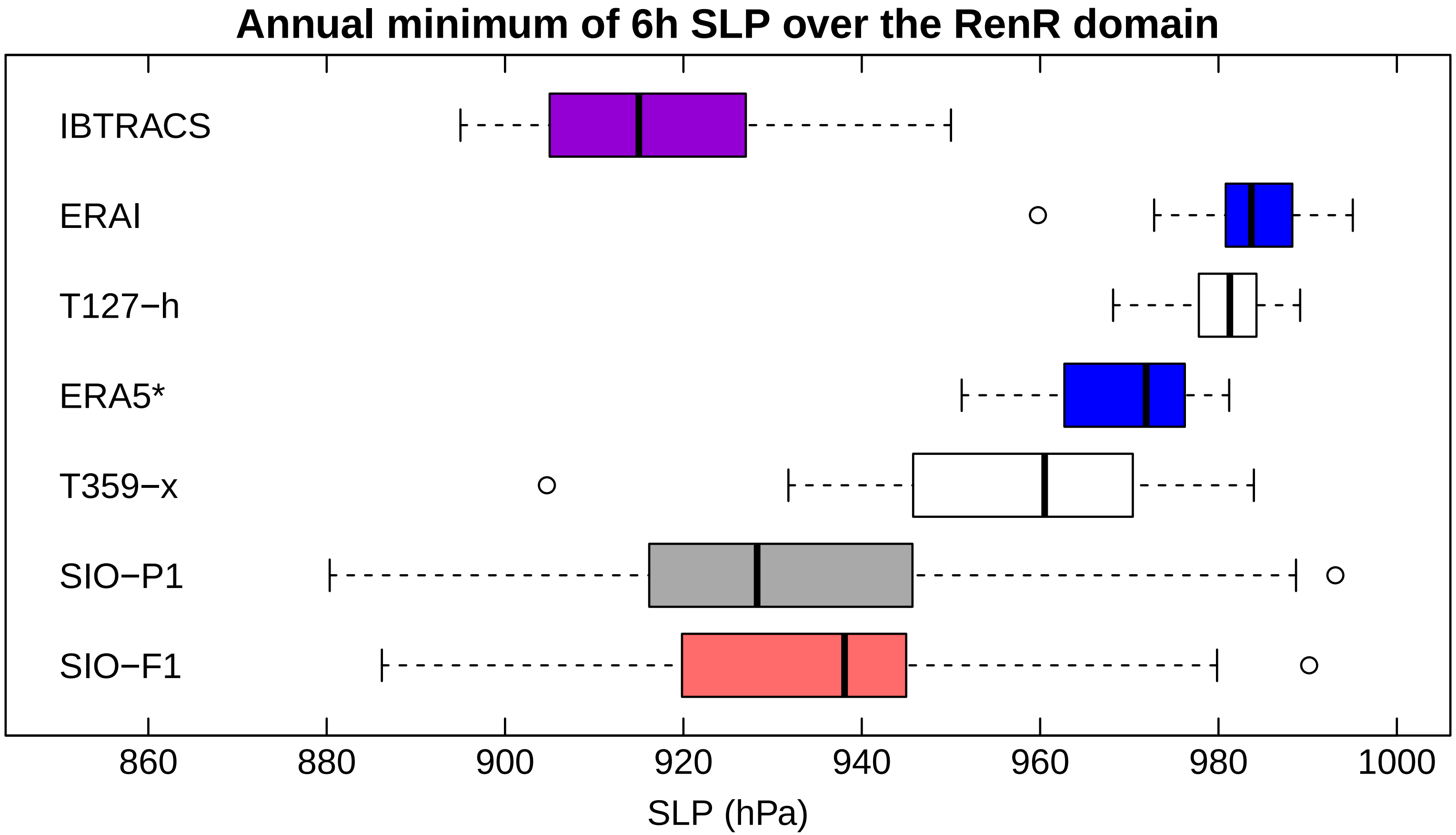

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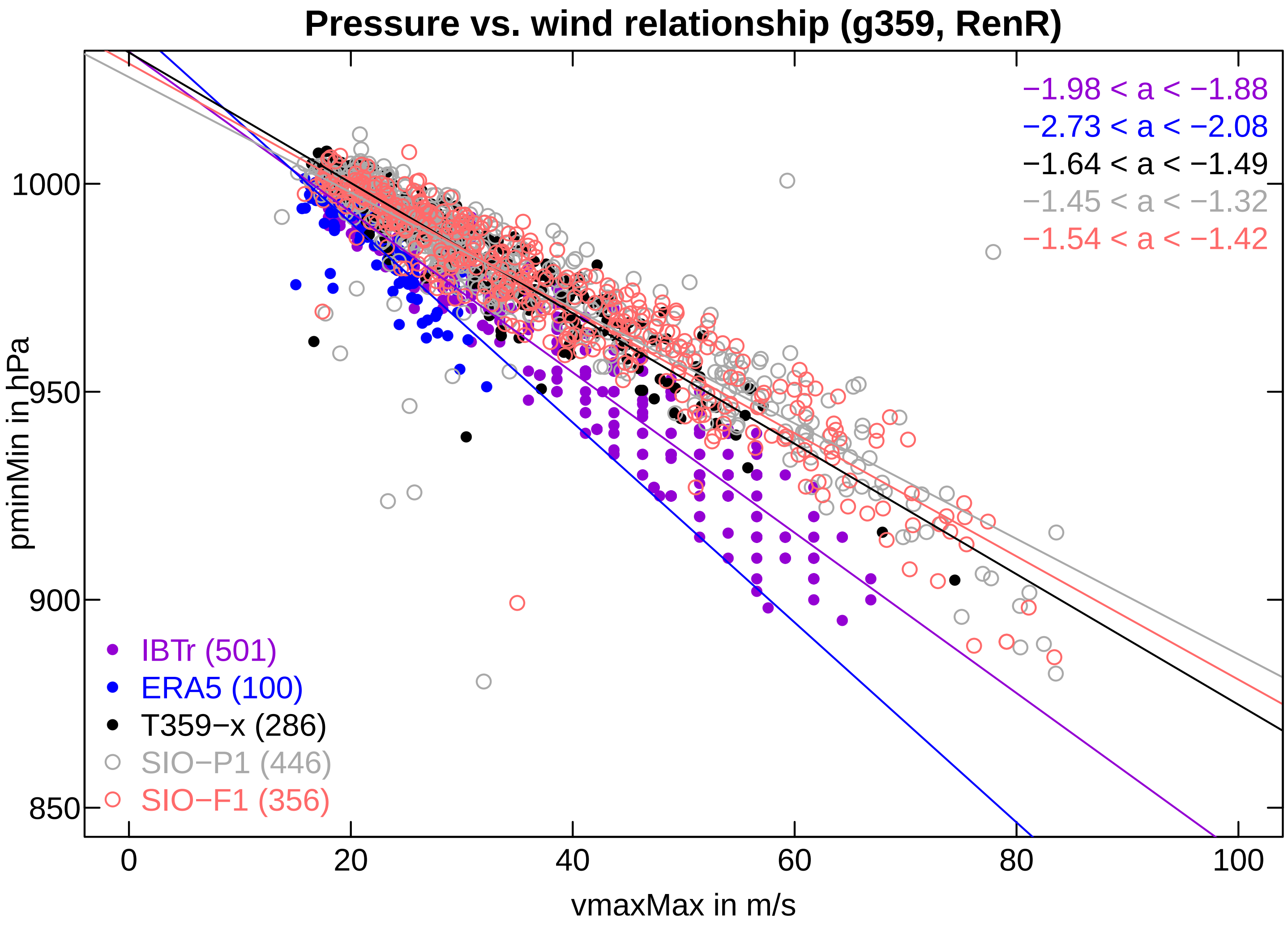
Pressure vs. wind relationship

- Winds for a given pressure seem to be stronger in ARPEGE.



Minimum SLP vs. maximum wind speed along the track.
Each dot is a system — systems differ between IBTRACS/ERA5 and ARPEGE.

Option B: cyclogenesis indices (CGIs)

- Idea: relate statistics of cyclone activity to the local environmental fields that can be simulated by common climate models.

- Generic formulation: $\mathrm{CGI} = \beta \times F(x_i) \times G(y_j)$,

with:
– β calibration parameter;
– $F()$ function of dynamical environmental variables x_i;
– $G()$ function of thermal environmental variables y_j.

- Computed at each gridpoint and month, calibrated over a reference period.

- $F()$ and $G()$ based on empirical relationships fitted in a present-day climate.

In general, they are multiplicative functions:
$F(x_i) = \prod_i f_i(x_i) \equiv \prod_i X_i$ and $G(y_j) = \prod_j g_j(y_j) \equiv \prod_j Y_j$.

Examples of CGIs

- Royer et al. (1998):

$$\mathrm{CYGP} = \beta_{\mathrm{CYGP}} \times \underbrace{|f| \left(\zeta_r \frac{f}{|f|} + 5\right) (V_{\mathrm{shear}} + 3)^{-1}}_{\text{dynamic}} \times \underbrace{\max(P_c^* - 3, 0)}_{\text{thermal}}$$

- Emanuel and Nolan (2004):

$$\mathrm{GPI} = \beta_{\mathrm{GPI}} \times \underbrace{\left|10^5 \zeta\right|^{3/2} (1 + 0.1 V_{\mathrm{shear}})^{-2}}_{\text{dynamic}} \times \underbrace{\left(\frac{H}{50}\right)^3 \left(\frac{V_{\mathrm{pot}}}{70}\right)^3}_{\text{thermal}}$$

- Tippett et al. (2011):

$$\mathrm{TCS} = \beta_{\mathrm{TCS}} \times \underbrace{\cos\varphi \cdot \exp\left(1.03\zeta - 0.15 V_{\mathrm{shear}}\right)}_{\text{dynamic}} \times \underbrace{\exp\left(0.05H + 0.56 SST_{\mathrm{loc}}\right)}_{\text{thermal}}$$

with:

– f Coriolis parameter, φ latitude;

– ζ (ζ_r) absolute (relative) vorticity at 850 hPa;

– $V_{\mathrm{shear}} = \frac{\Delta V}{\Delta p}$ vertical wind shear between 850 and 200 hPa;

– P_c^* normalized convective precipitation;

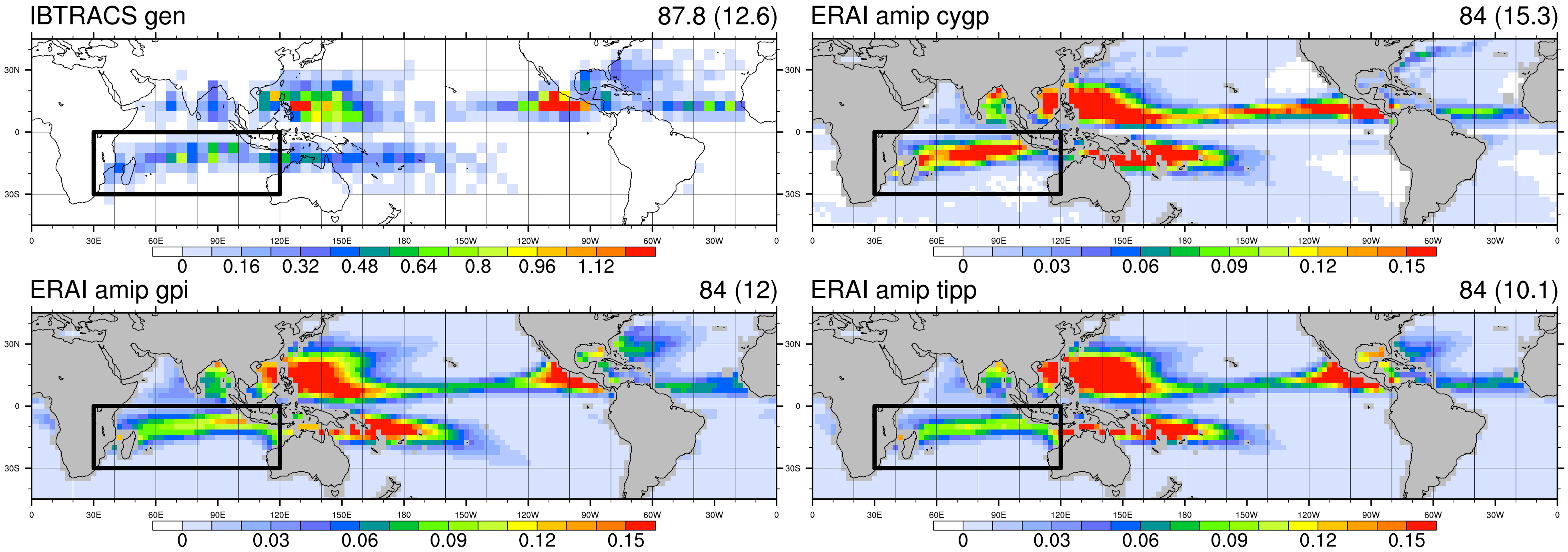
– H relative humidity at 600 hPa;

– $SST_{\mathrm{loc}} = \mathrm{SST} - \overline{\mathrm{SST}}^{[20S-20N]}$ local SST anomaly relative to the tropics;

– V_{pot} potential intensity = theoretical maximal TC wind (Emanuel 1988).

Validation of CGIs – 1/2

- CGIs represent cyclogenesis regions fairly well.

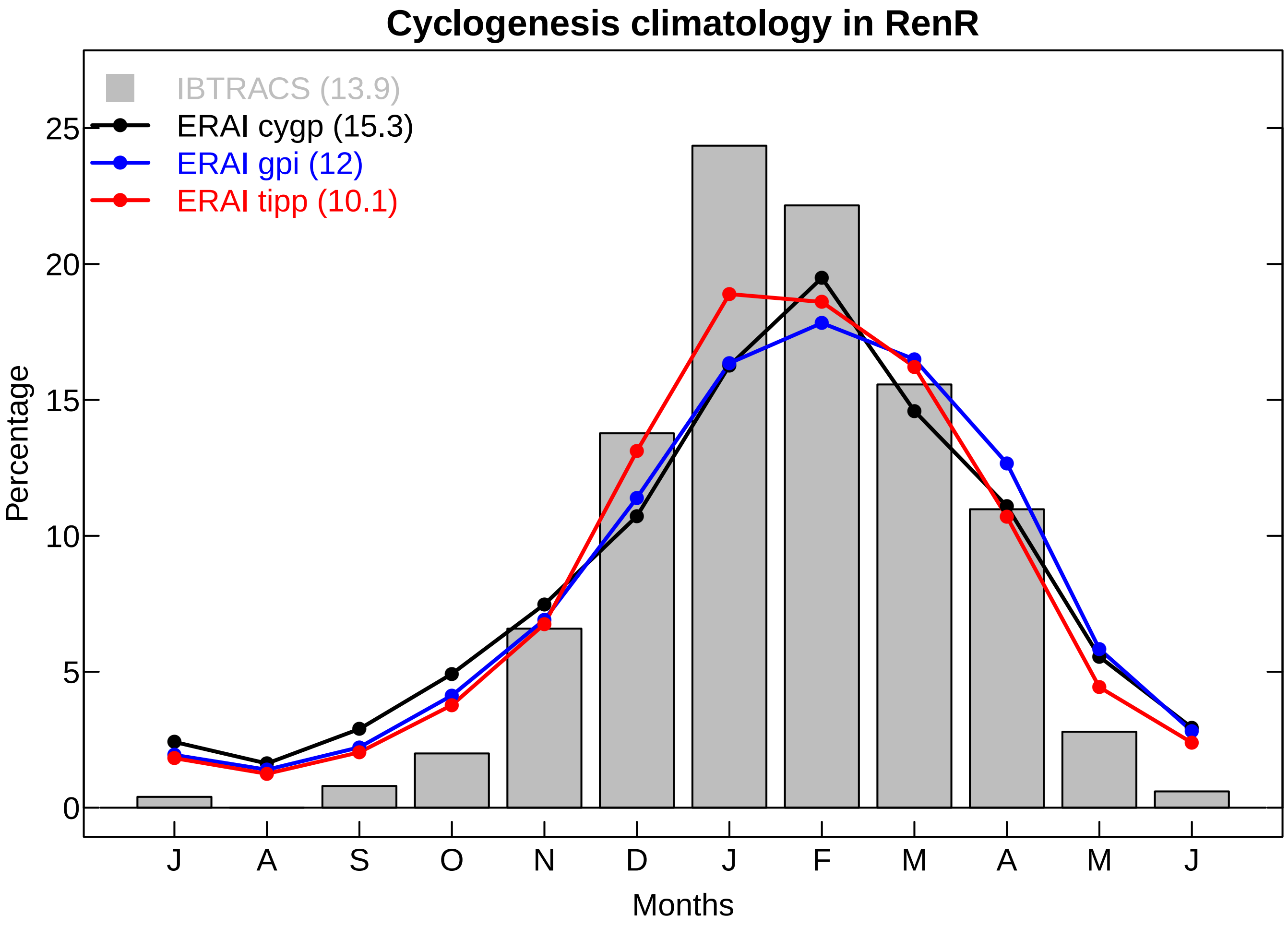


ERAI and IBTRACS 1979–2016.
CGIs are calibrated at 84 TCs per year.

N.B. For a more comprehensive evaluation, see Menkes et al. (2011).

Validation of CGIs – 2/2

- CGIs represent cyclogenesis seasons fairly well.



ERAI and IBTRACS 1979–2016

N.B. For a more comprehensive evaluation, see Menkes et al. (2011).

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IPCC-AR5: less frequent, more intense

- Assessed from (only) the few high-resolution atmospheric simulations.
- Theory poorly understood, observations insufficient.

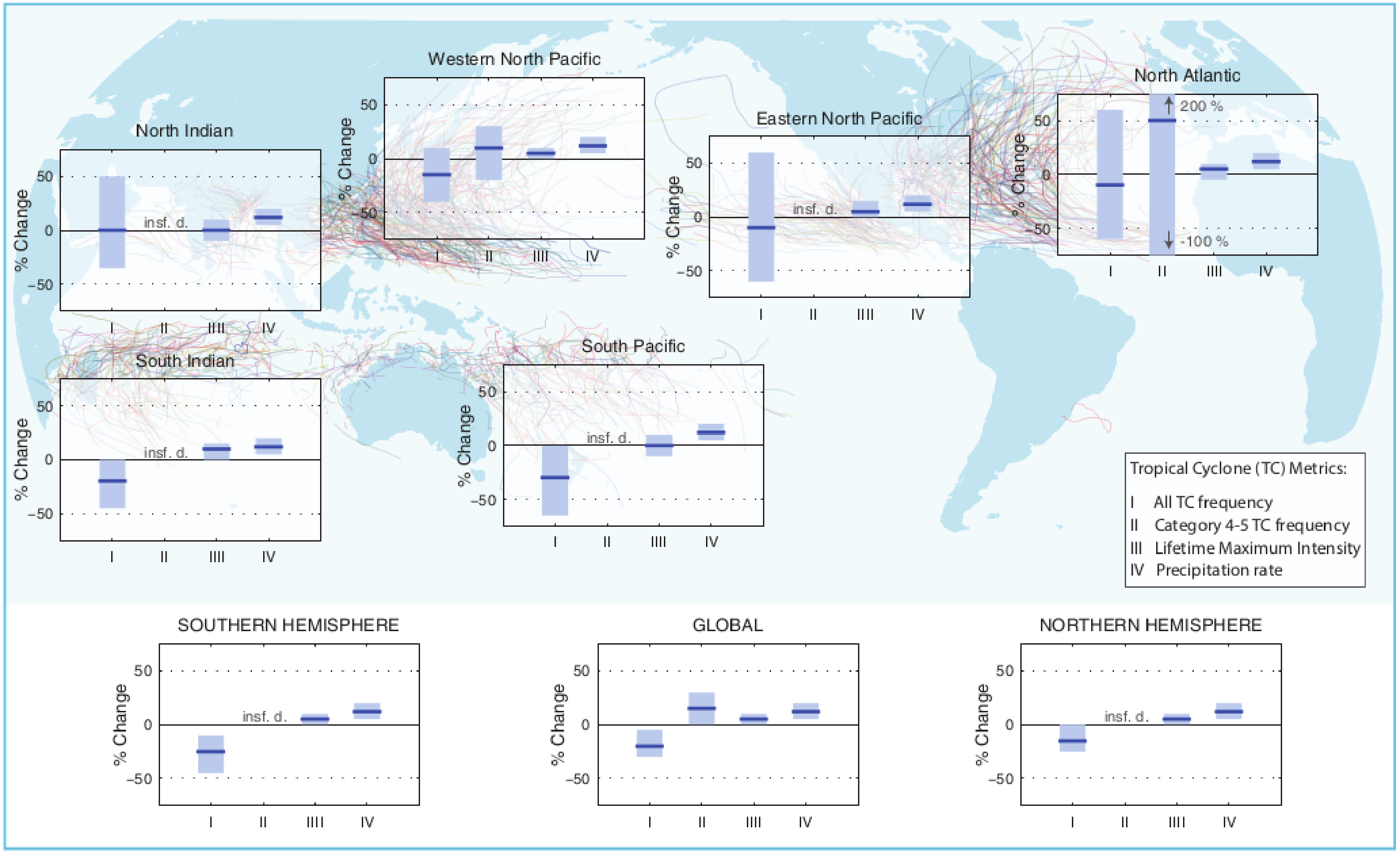
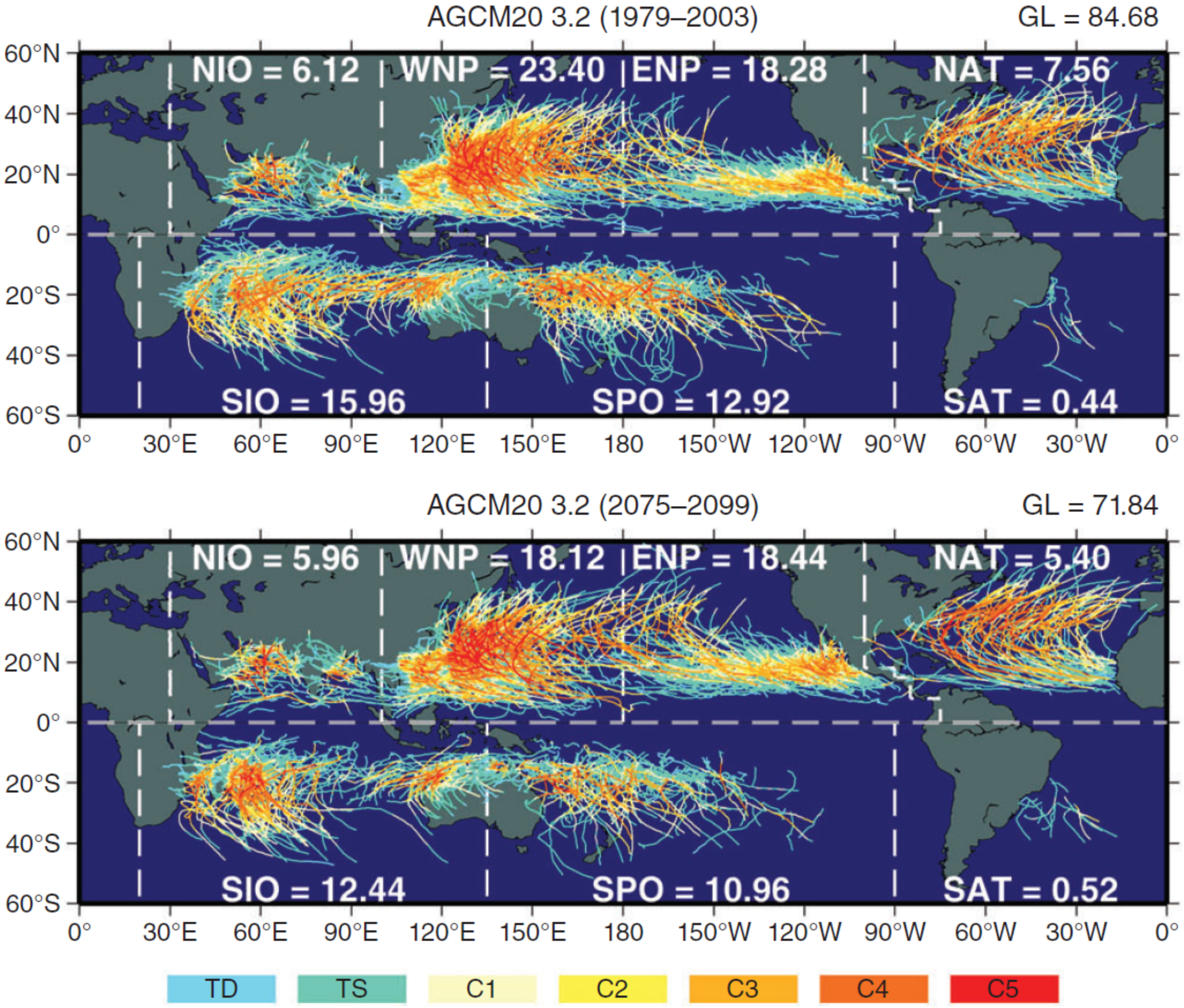


Figure 14.17 | General consensus assessment of the numerical experiments described in Supplementary Material Tables 14.SM.1 to 14.SM.4. All values represent expected percent change in the average over period 2081–2100 relative to 2000–2019, under an A1B-like scenario, based on expert judgement after subjective normalization of the model projections.

Ⓒ IPCC AR5 (2013), Section 14.6.1.

Example of results from high-resolution simulations

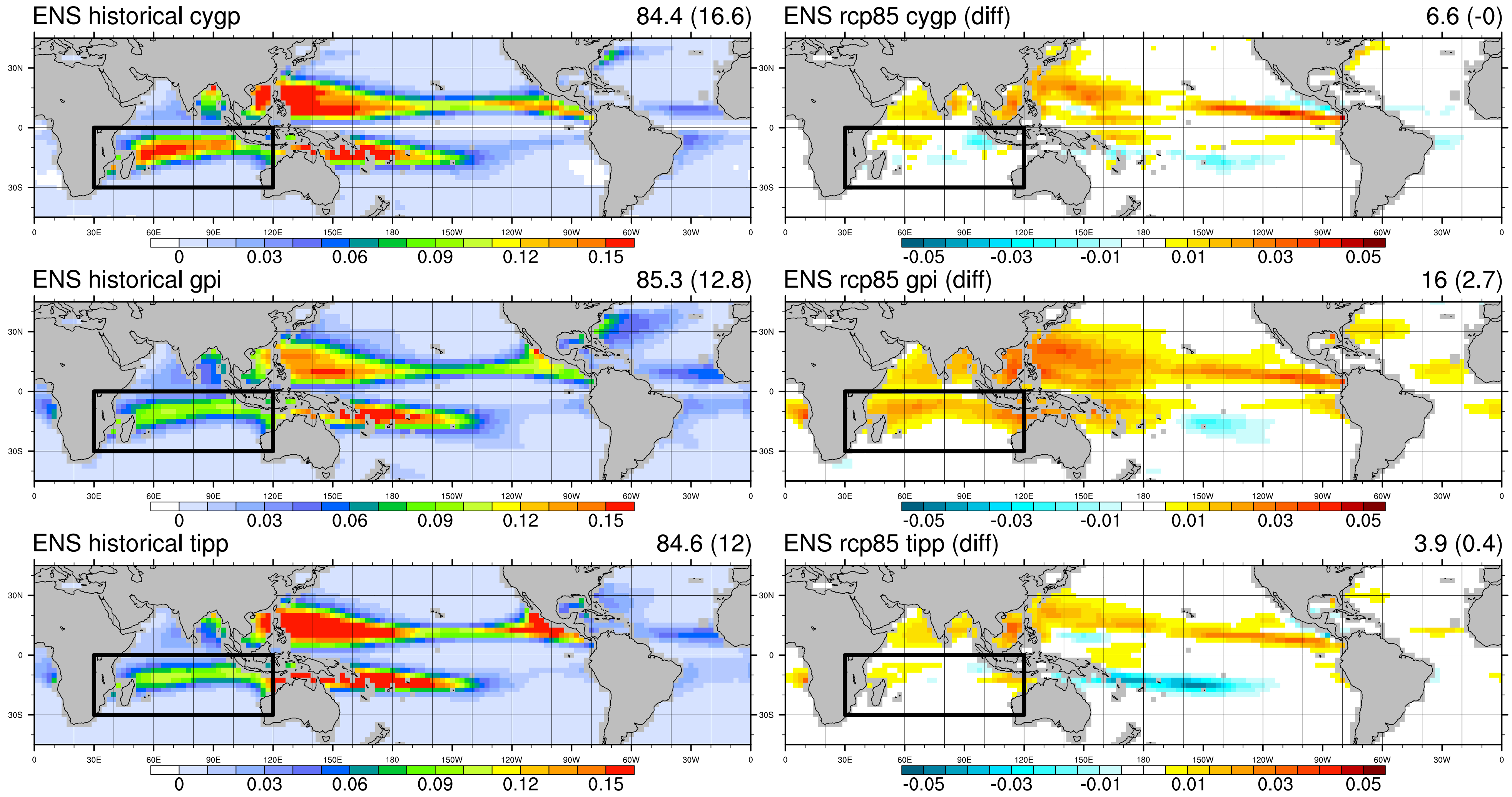
- Classical approach: count TCs in present-day vs. future simulations.



© Walsh et al., Clim. Change, 2015 (review paper).

CGIs applied to the CMIP5 multi-model ensemble

- CMIP5 models project an overall increase in CGIs.
  - consistent with the literature (e.g., Royer and Chauvin (2009)),
  - inconsistent with HR simulations (e.g. Camargo (2014)).



Multi-model mean of 14 models. Clim over 1976–2005 and difference with 2070-2099 (RCP8.5).
CGIs are calibrated at 84 TCs/yr over the whole historical run (1900–2005).

Individual contributions to changes in CGIs

- Recall: $\mathrm{CGI} = \beta \times F(x_i) \times G(y_j) = \beta \times \prod_i X_i \times \prod_j Y_j$.

- Changes $\Delta\mathrm{CGI} = \mathrm{CGI}^{\mathrm{fut}} - \mathrm{CGI}^{\mathrm{pre}}$ can thus be broken down into:

$$\frac{\Delta\mathrm{CGI}}{\mathrm{CGI}^{\mathrm{pre}}} = \underbrace{\sum_i \frac{\Delta X_i}{X_i^{\mathrm{pre}}}}_{\text{dynamic}} + \underbrace{\sum_j \frac{\Delta Y_j}{Y_j^{\mathrm{pre}}}}_{\text{thermal}} + \varepsilon$$

i.e.:

$$\Delta\mathrm{CGI} = \underbrace{\sum_i \frac{\Delta X_i}{X_i^{\mathrm{pre}}} \cdot \mathrm{CGI}^{\mathrm{pre}}}_{\text{dynamic}} + \underbrace{\sum_j \frac{\Delta Y_j}{Y_j^{\mathrm{pre}}} \cdot \mathrm{CGI}^{\mathrm{pre}}}_{\text{thermal}} + \varepsilon'$$

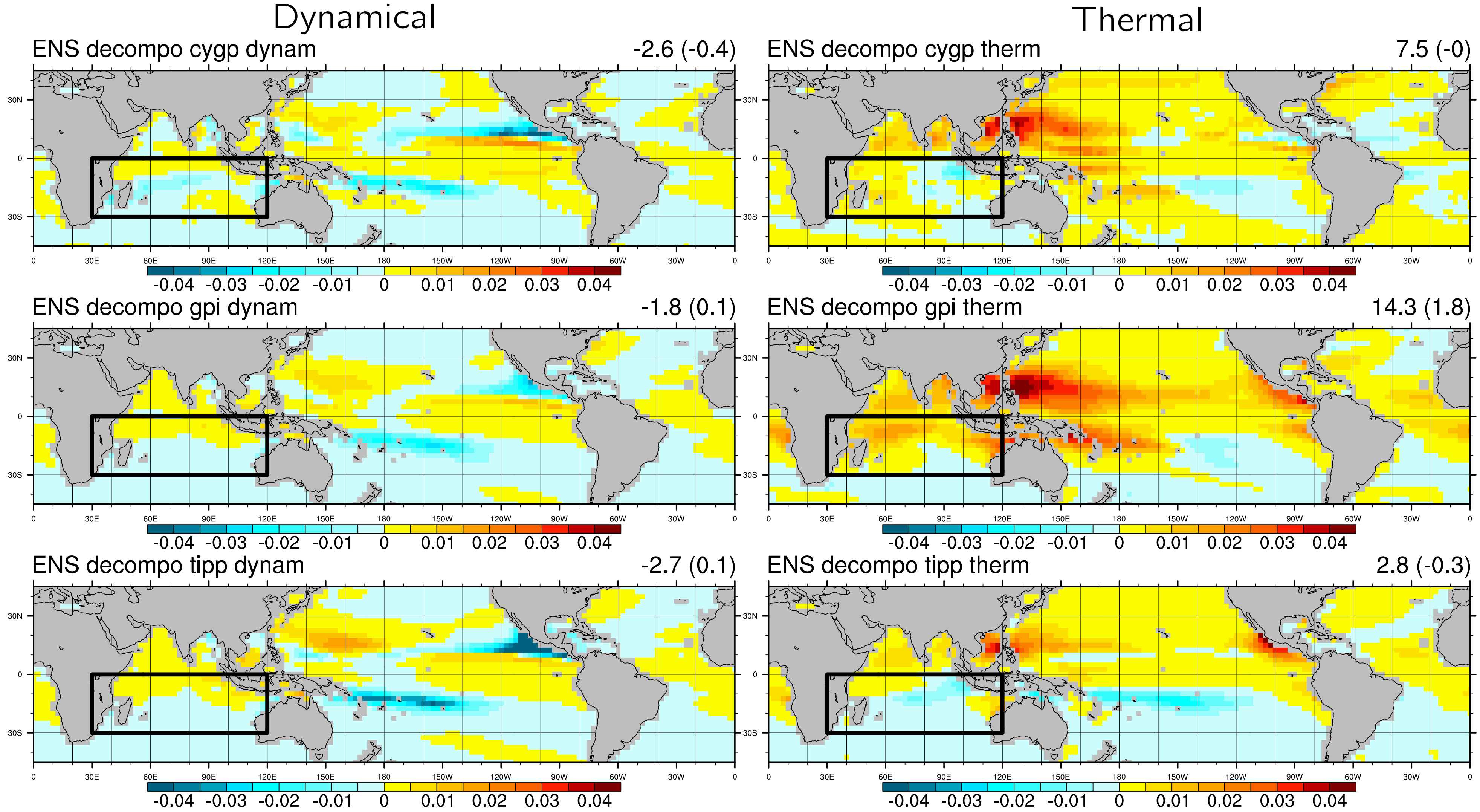
with :

– $\frac{\Delta X_i}{X_i^{\mathrm{pre}}} \cdot \mathrm{CGI}^{\mathrm{pre}}$ individual contribution of variable x_i;

– ε, ε' second-order terms.

Dynamical vs. thermal contributions

- Dynamical factors cause a slight decrease in CGIs ⟶ TC frequency?
- Thermal factors cause an increase in CGIs ⟶ TC intensity?



Decomposition is made for each model separately,
and then averaged over the ensemble (14 models).

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Experimental set-up

- Simulations performed*:

PRE625REFT359x (**T359-x**):
1979–2010, uniform T359 grid, SST from observations.

P625SIOT359srP1 (**SIO-P1**):
1965–2014, SIO-stretched T359 grid, SST from CNRM-CM5 historical run.

P625SIOT359srF1 (**SIO-F1**):
2045–2094, SIO-stretched T359 grid, SST from CNRM-CM5 RCP8.5 run.

- Reference for validation: **IBTRACS** over 1979–2016, **ERA5** over 2009–2018.

- All data are interpolated onto a common 0.5° grid prior to tracking.

- Other simulations that could be made**:

– PRE625REFT359x-P1/F1, i.e. with SST from CNRM-CM5 runs;
– P625SIOT359srO1,i.e. with SST from observations;
– P625SIOT359sr[P,F][2,3,4...], i.e more members.

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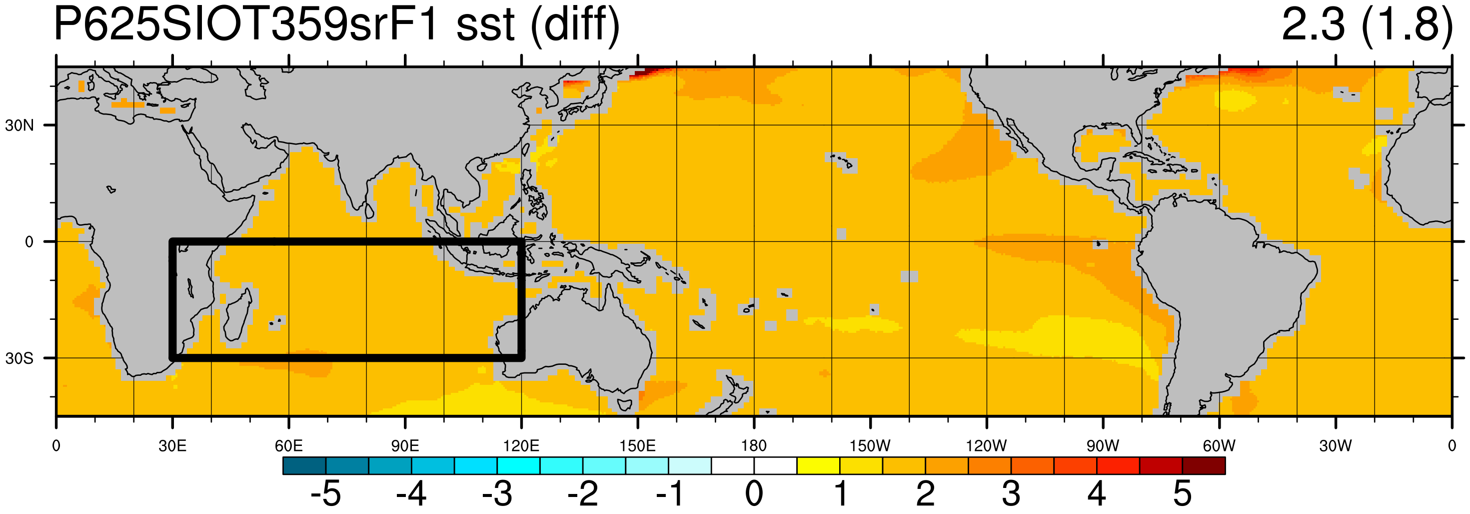
* by F. Chauvin.
** anyone interested?

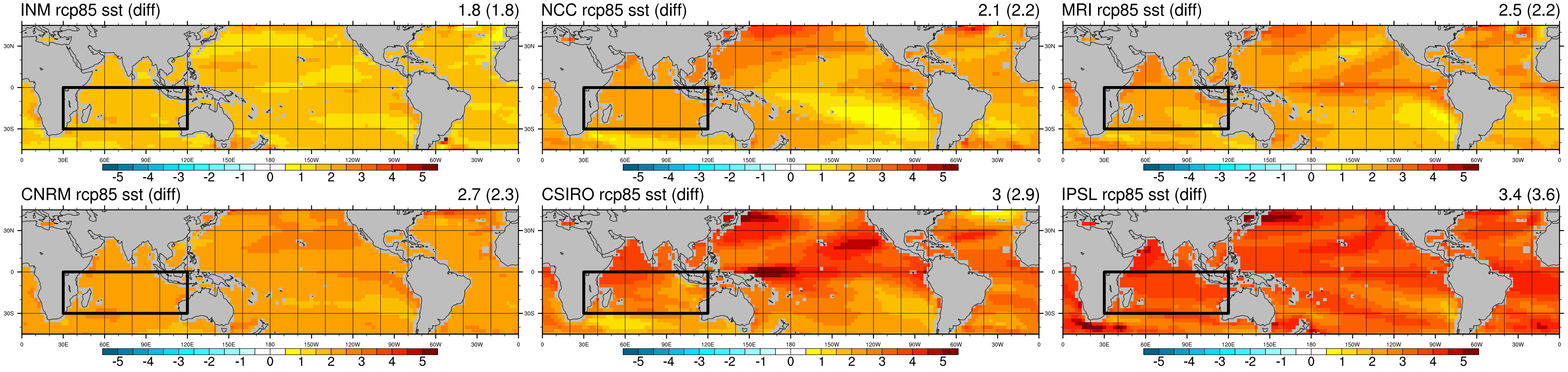
SIO-F1 vs SIO-P1 SST

- Quasi-uniform 2 °C warming in the SIO basin.
- CNRM-CM5 is close to the CMIP5 ensemble mean.

SST 2045–2094 (RCP8.5) vs. 1965–2014 in CNRM-CM5



SST 2070–2099 (RCP8.5) vs. 1976–2005 in a subset of CMIP5 models

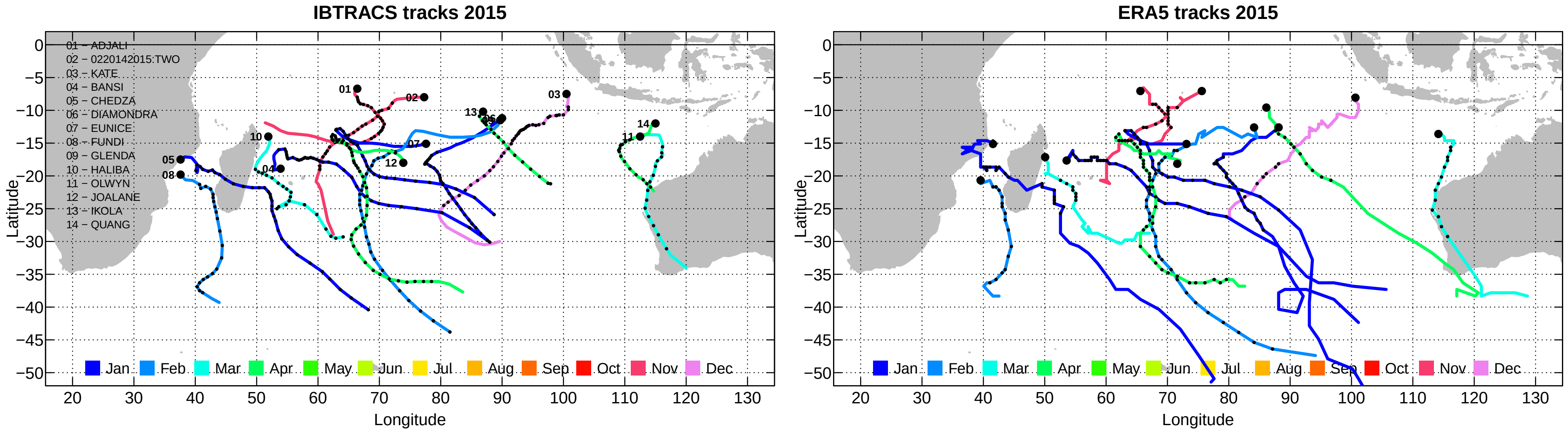


Tracking algorithm

- Chauvin et al. (2006):
  - detection of candidates (criteria on SLP, T, U, V and vorticity);
  - construction of TC tracks (association between consecutive time steps);
  - completion of tracks before and after the TC phase (criterion on vorticity).

- Validation/calibration made on ERA5 vs. IBTRACS.
  - e.g., retained wind threshold for detection = 13 m/s.

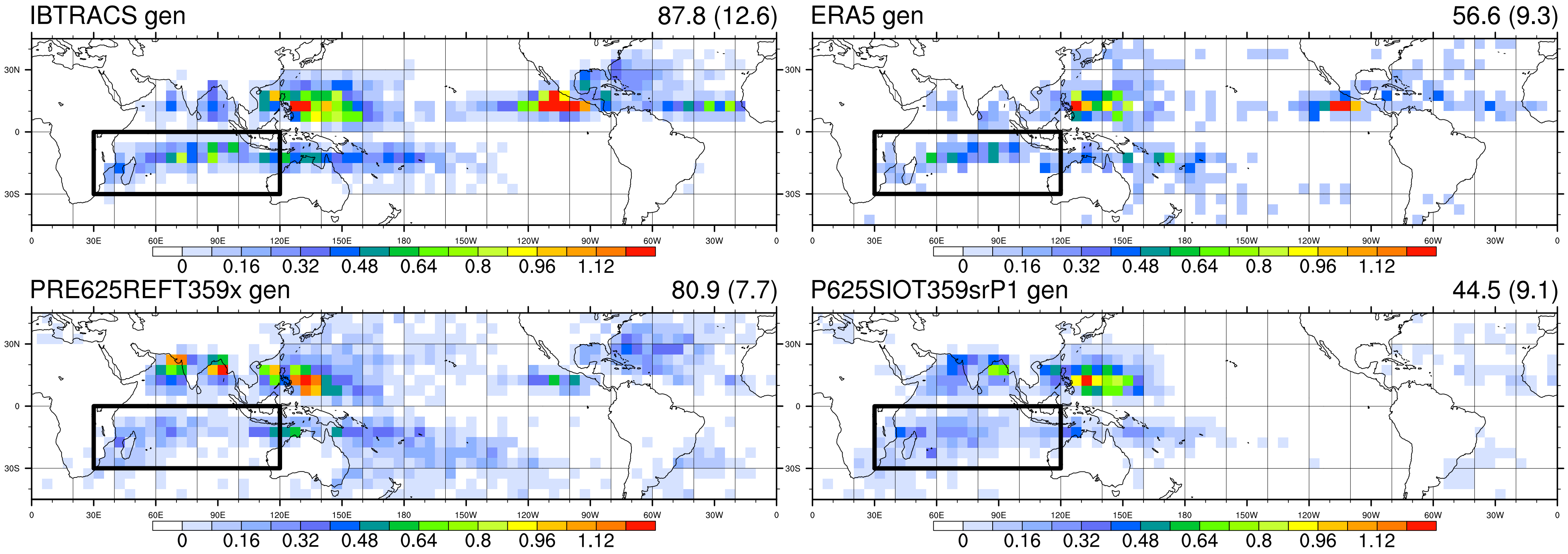
Example of observed vs. detected tracks in 2015 over the SIO basin



Densities of tracks – Validation

- Number in the SIO roughly OK but biases in the spatial pattern.
- Difficulties when comparing with IBTRACS + noise due to internal variability.

Density of track genesis (1 point per track)



Clim over various periods (!). Counts in 5×5° boxes.

Densities of tracks – Validation

- Number in the SIO roughly OK but biases in the spatial pattern.
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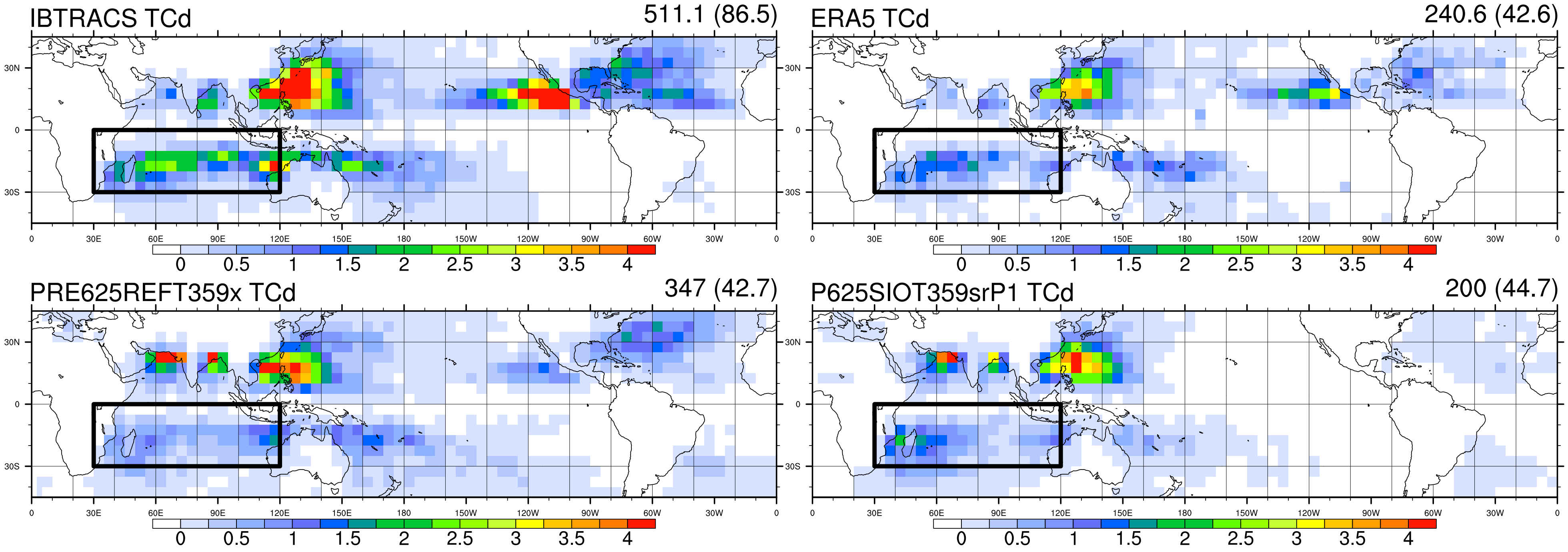
Density of TC points (several points per track)

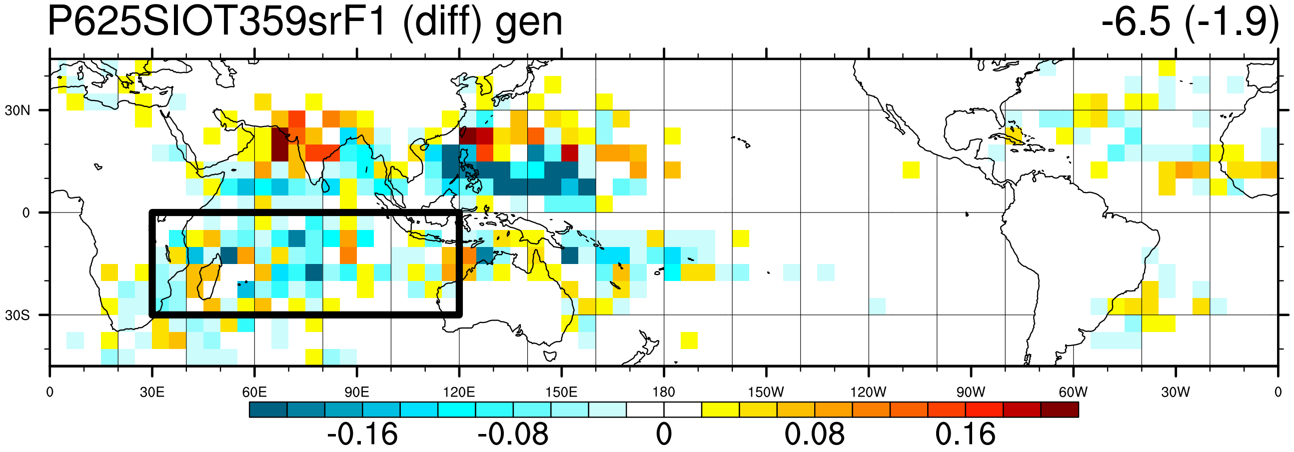


Clim over various periods (!). Counts in 5×5° boxes.

Densities of tracks – Climate change

- Decrease in the number of TCs and TC days by ∼20 %.
- The signal seems to be larger over the SWIO (to be confirmed).

Density of track genesis (1 point per track)



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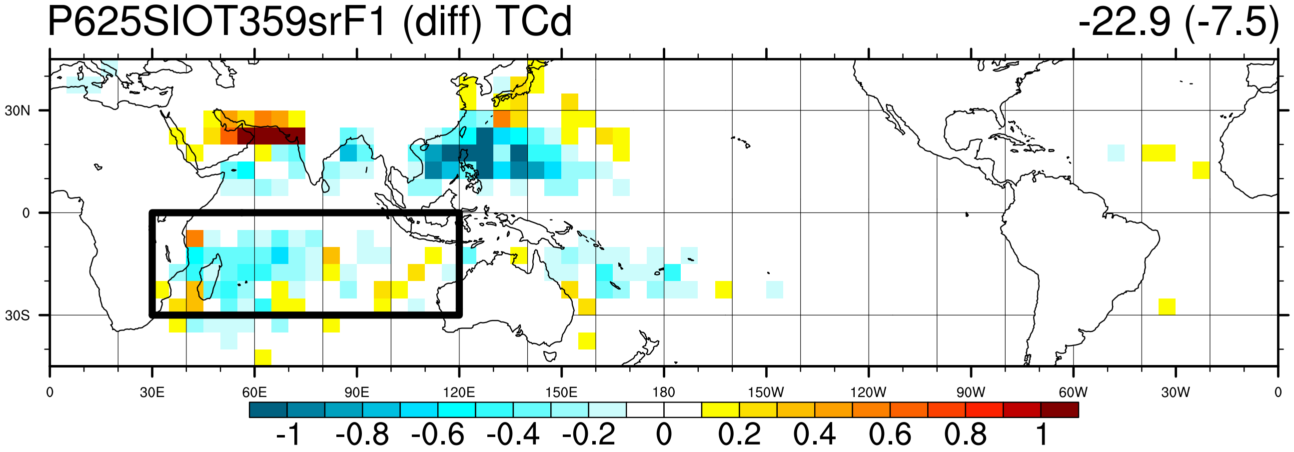
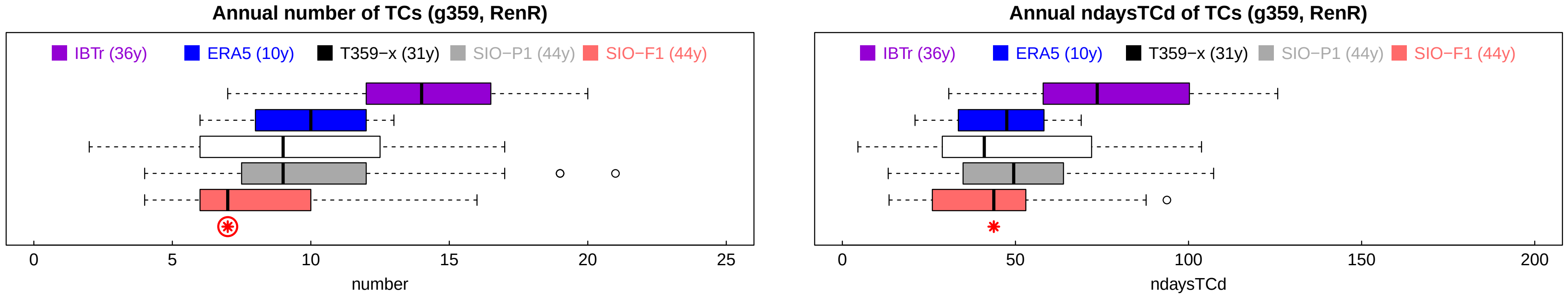
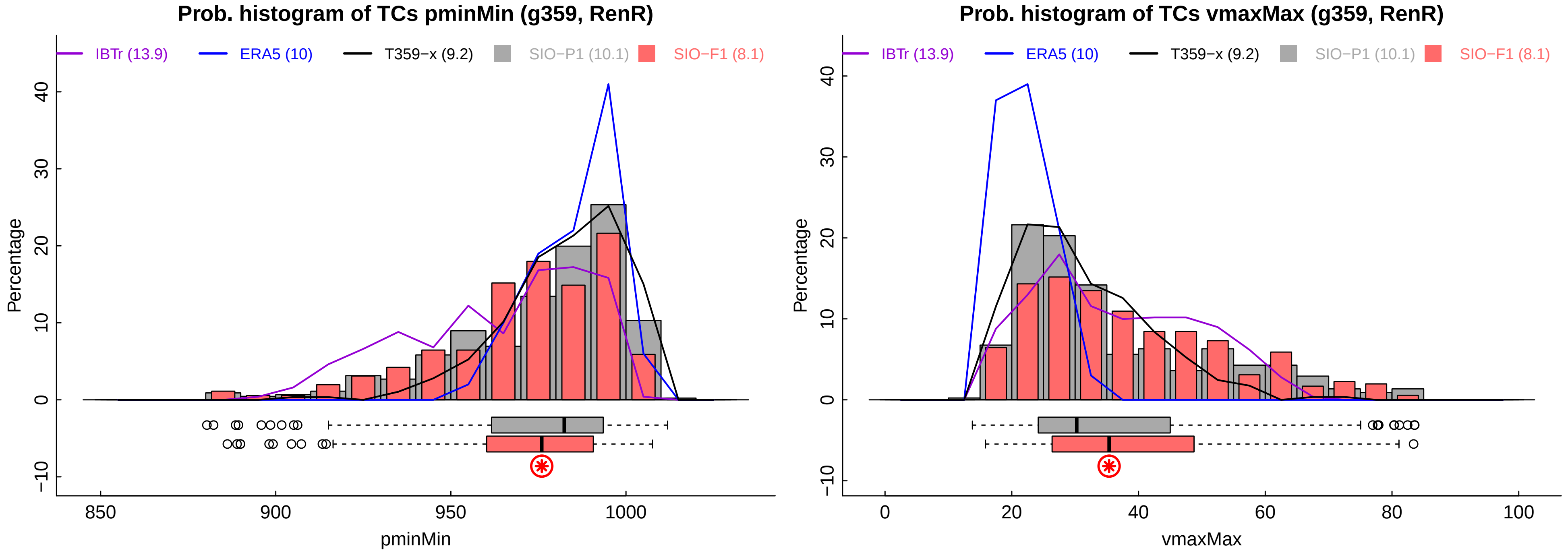


Less frequent, more intense

Annual number of TCs (left) + number of TC days (right)



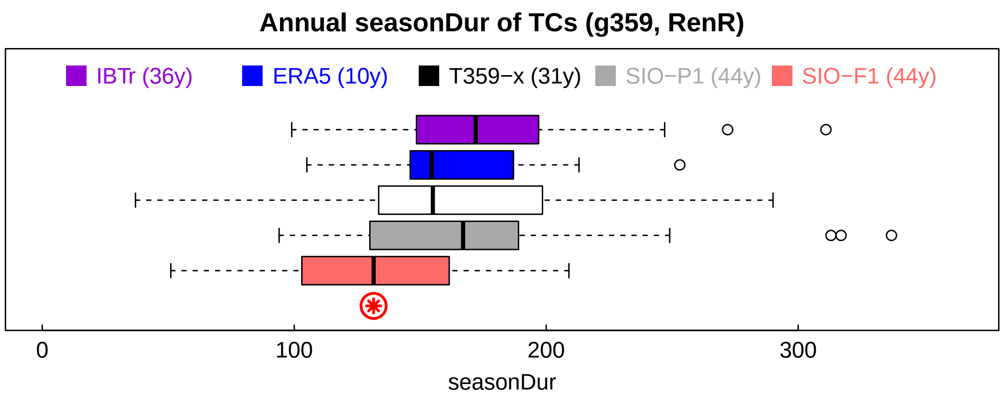
Probability histogram of min SLP (left) + max wind (right)

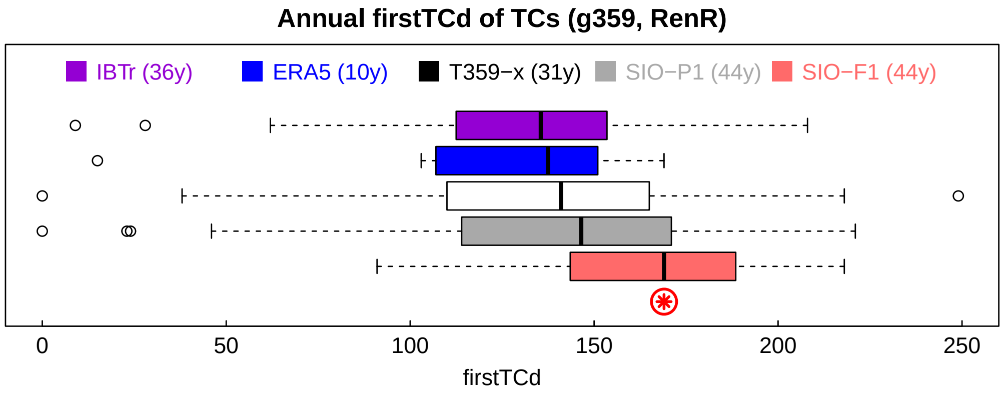


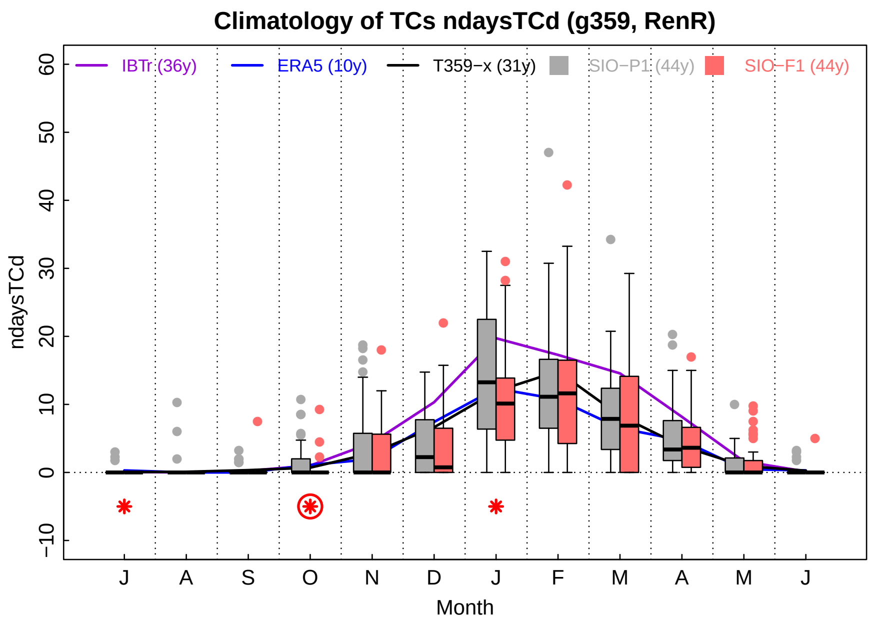
Stars indicate that the SIO-P1 vs. SIO-F1 difference is statistically significant.

Other significant changes

- The maximum lifetime intensity is slightly shifted poleward (1° of lat).
- The intensification phase is slightly shorter: 1.75 ⟶ 1.5 days.
- The TC phase is slightly longer: 4.25 ⟶ 5 days.
- The **cyclonic season** is shorter (170 ⟶ 140 days), mainly because it starts later (Nov 15 ⟶ Dec 15):





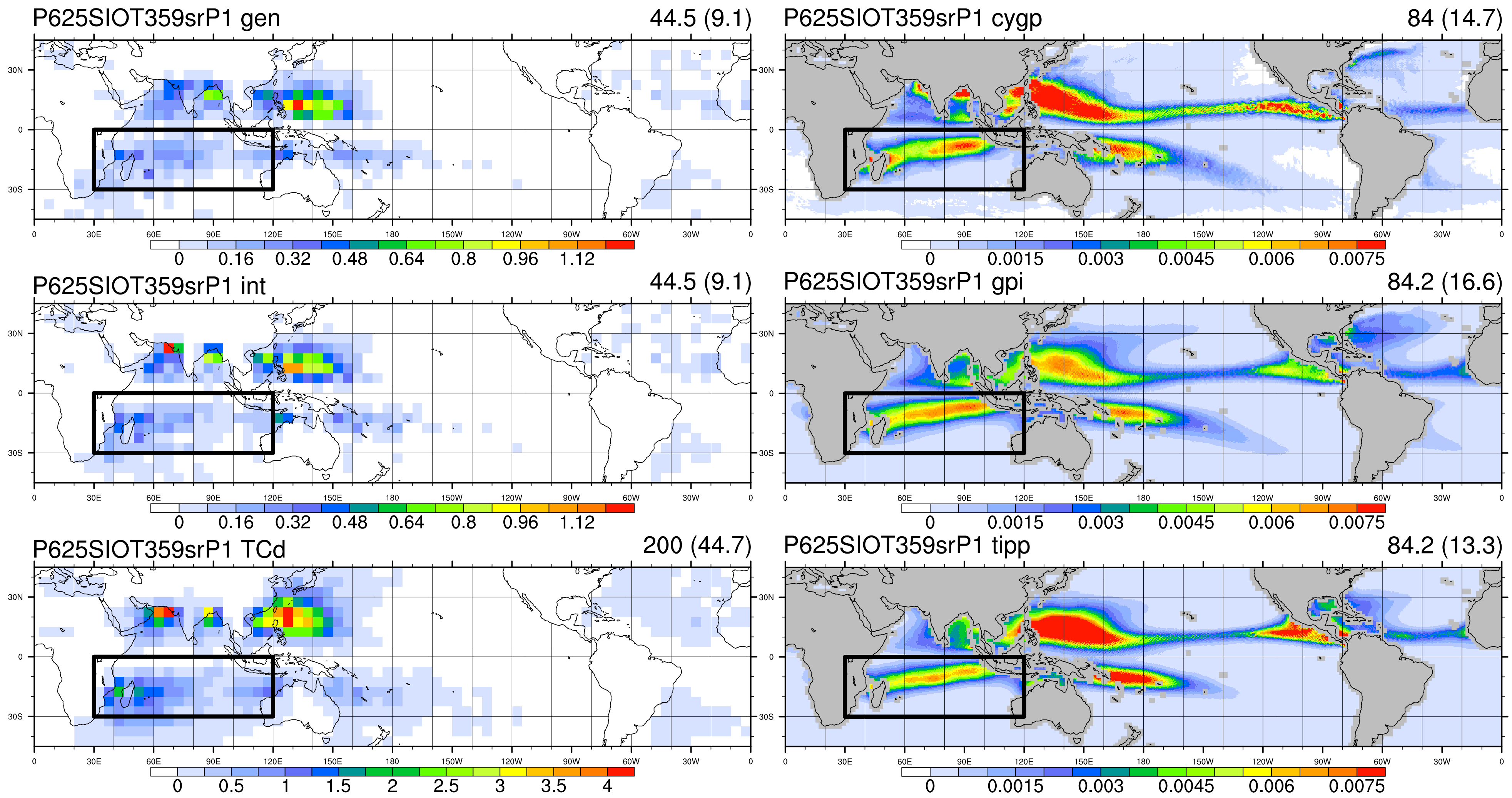


Stars indicate that the SIO-P1 vs. SIO-F1 difference is statistically significant.

CGIs applied to ARPEGE experiments

- In the SIO, cyclogenesis "should be" more localized according to CGIs.

Actual track densities CGIs

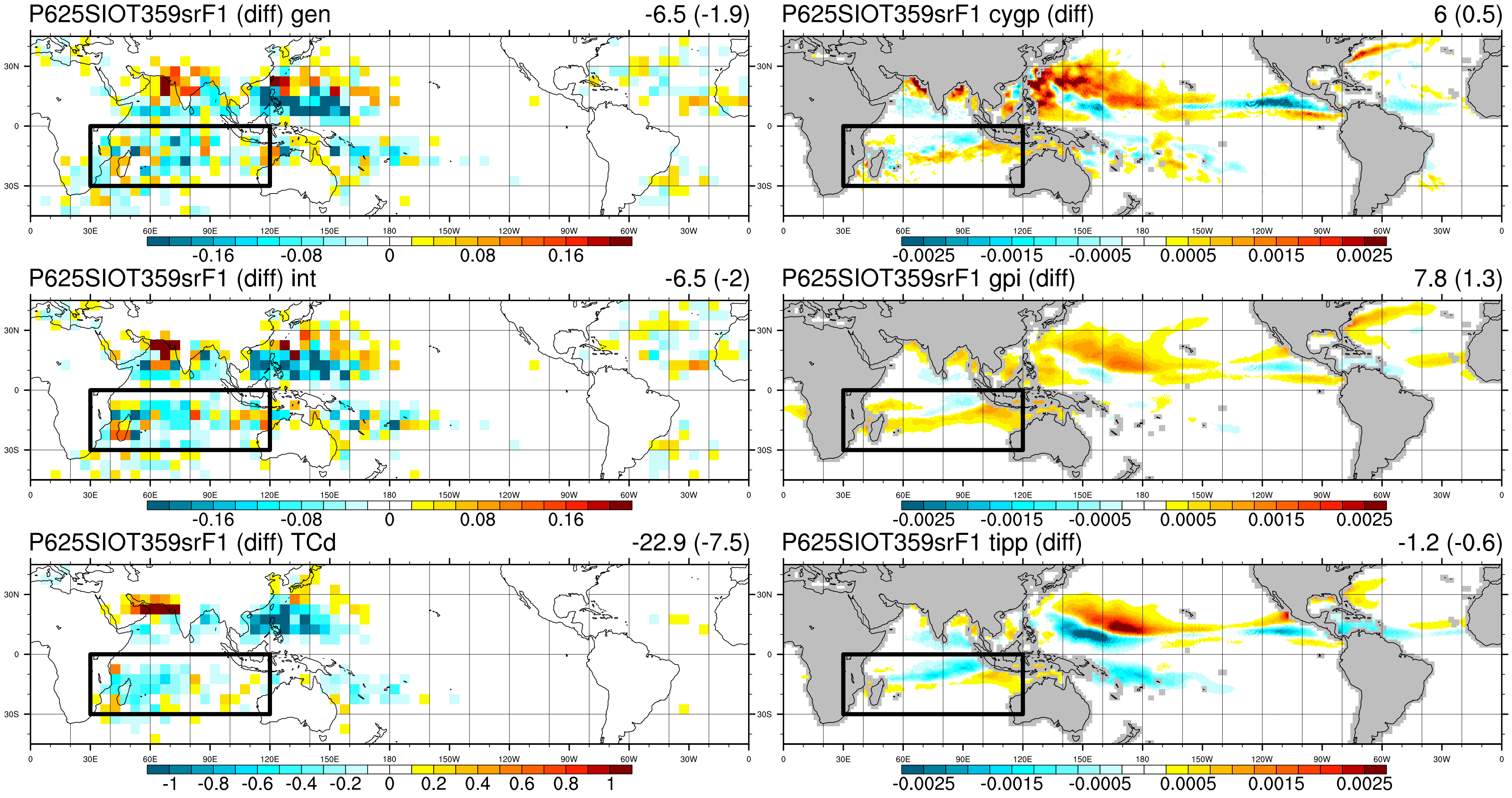


CGIs applied to ARPEGE experiments – Climate change

- CGIs indicate a slight increase and poleward shift in the cyclogenesis.

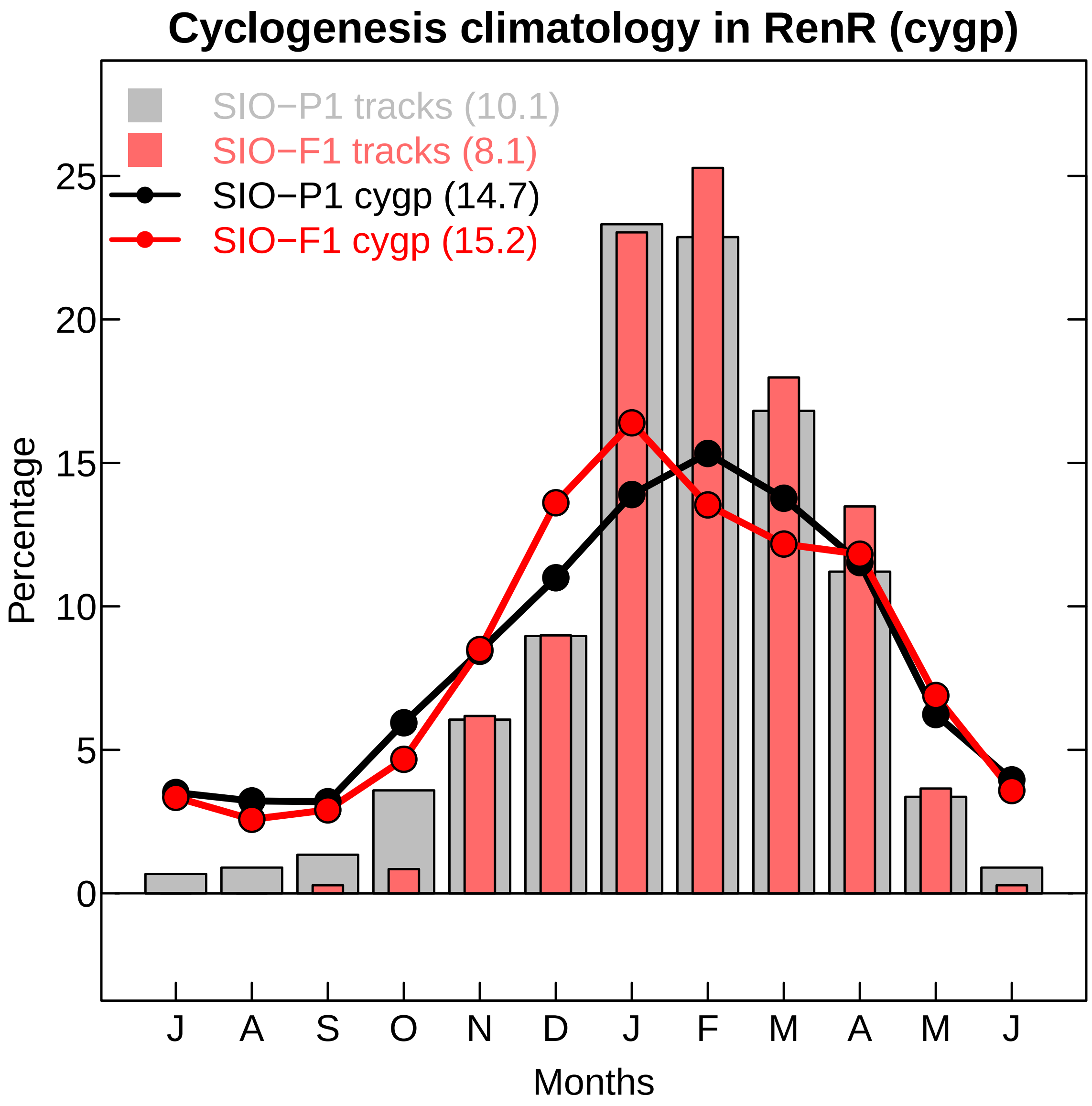
Actual track densities

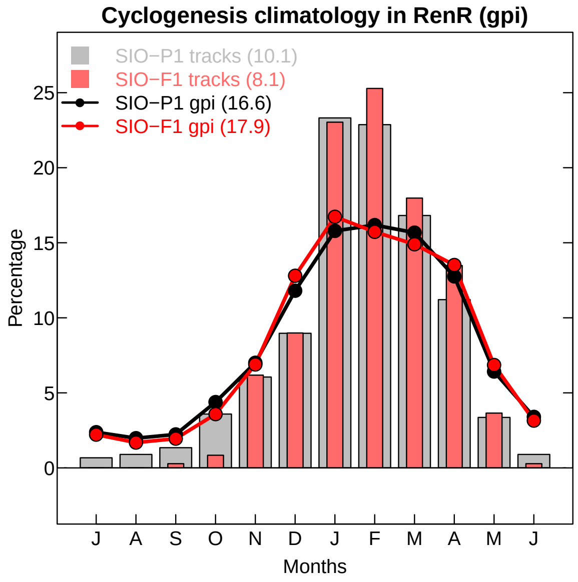
CGIs



Changes in seasonal timing

- CGIs seem to slightly decrease at the beginning of the season.


Cyclogenesis climatology in RenR (cygp)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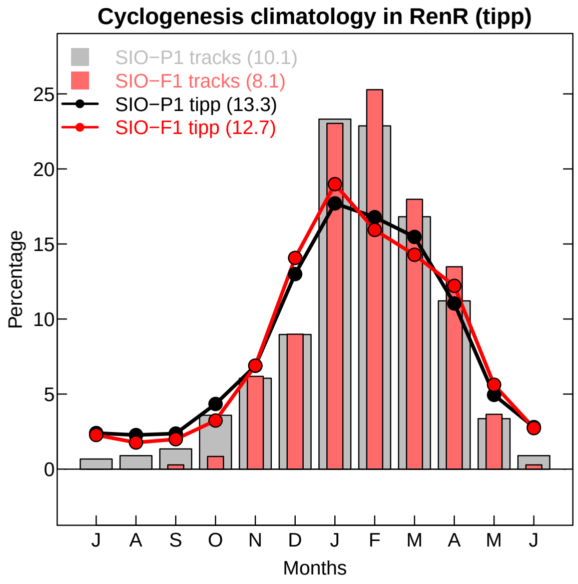
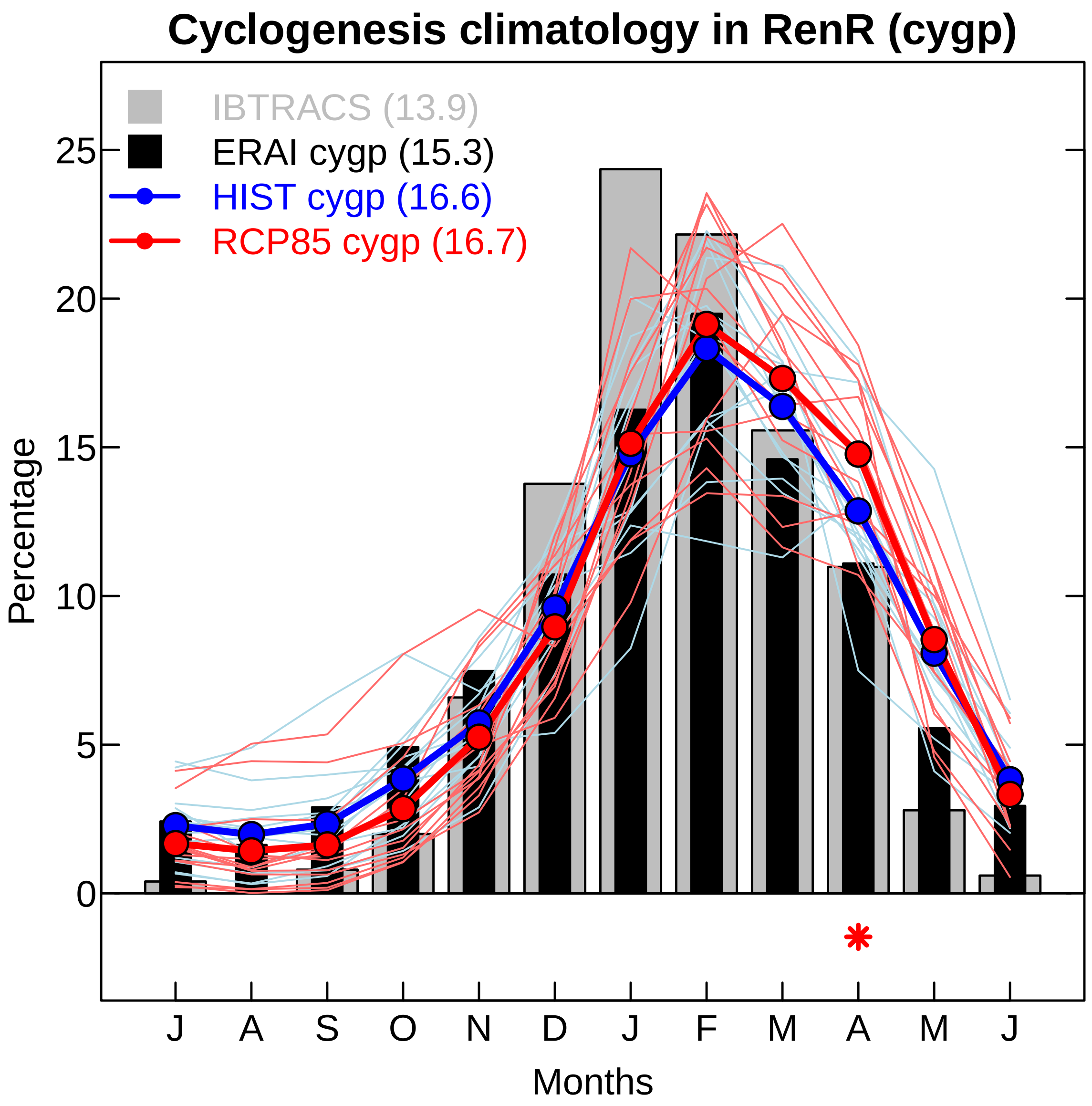

Cyclogenesis climatology in RenR (tipp)

Changes in seasonal timing – CMIP5

- This result in also found in the CMIP5 multi-model ensemble.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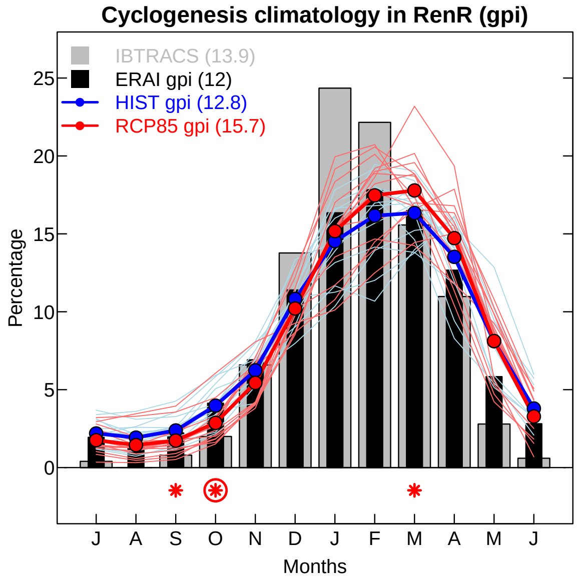
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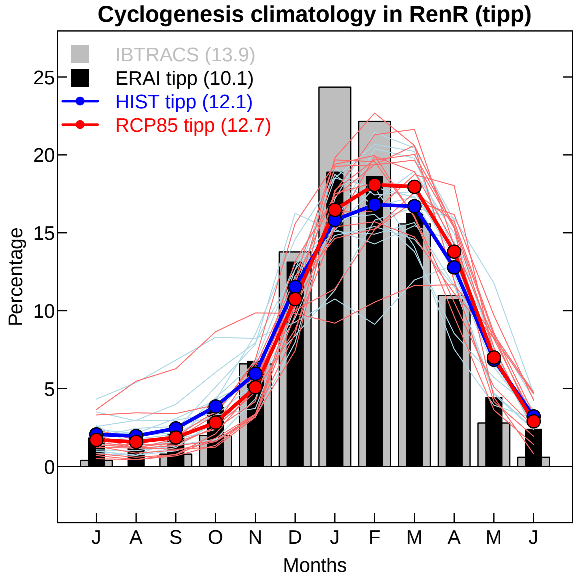
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Conclusions

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SIO TCs are found to be less frequent / more intense in a warmer climate.

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But they might explain some aspects of TC changes (e.g. season duration).

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– further understand the decrease in TC frequency: investigate the genesis and intensification of intial vortices (Chia-Lun's work with J.-P. Duvel's tracker).
– further document TC changes (e.g. associated rainfall, link with MJO, etc.).
– further assess the link between TCs and cyclogenesis indices.
– compute additional members to improve the signal-to-noise ratio?

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– compute additional members to improve the signal-to-noise ratio?

Longer-term prospectives:
– explore statistical learning for tracking TC in reanalysis / model data.
– develop cyclogenesis indices that can be relevant for climate change.
– analyse the CMIP6 multi-model database, esp. models with resolution < 50km.