Tropical Cyclone prediction and projection

CMCC Foundation - CSP Division -

Enrico Scoccimarro

Tropical Cyclones and climate

Tropical cyclones (TCs) in their most intense expression (hurricanes or typhoons) are the most spectacular and deadly geophysical phenomena. Strong wind, storm surge and extreme precipitation are the main factors determining TC destructiveness and TC related annual worldwide damage is of the order of billions of dollars and a death toll of thousands of people. The huge TC impact in countries dealing with TCs make our ability in modelling TCs a key issue to better understand their interaction with the climate system and to verify their predictability. In the past 10 years CMCC CSP division developed a series of General Circulation Models able to represent such events, making CMCC an active actor in the TC research contest with a special focus on prediction and projections.

TCs are classified mainly based on the associated 10-meter sustained wind speed. The yearly averaged number 90 is obtained adding annual number of Tropical Storms (wind speed greater than 17.5 m/s) and hurricanes/typhoons (wind speed greater than 33 m/s). Strong TCs are named “hurricanes” or “typhoons” depending on the location where they form: the term “hurricane” is used in the Atlantic and Northeast Pacific – “typhoon” is used in the Northwest Pacific – “cyclone” is used in the Southern Hemisphere. Hurricane classes range from category 1 (at least 33 m/s) to category 5 (greater than 70 m/s).

The Tropical Cyclone activity dependence on climate change started to be investigated with reasonably high-resolution models about 10 years ago, based on CMIP3 (3rd Coupled Model Intercomparison Project) results (Gualdi et al. 2008). One of the ways TCs play a role in the climate system is through their modulation of the meridional ocean heat transport (Scoccimarro et al., 2011, 2016), affecting the climate system thanks to the TC related surface wind stresses. Not only local (over the tropical belt) TC effects on the ocean are expected, but also effects on the large scale atmospheric circulation have been found in terms of provision of water content to high latitudes (Scoccimarro et al. 2018a) and interaction with the Arctic Ocean dynamics (Scoccimarro et al. 2012).

Tropical Cyclone representation in dynamical models

The main tool we use to model the interaction between TCs and the climate system are dynamical models, commonly known as General Circulation Models.

Figure 1 illustrates the observed TC tracks over the period 2005-2014 as resulting from the NOAA’s Tropical Prediction Center (Atlantic and eastern North Pacific tracks), and from the U.S. Navy’s Joint Typhoon Warning Center, compared to the results obtained tracking TCs in CMCC-CM2 General Circulation model output, running with two different horizontal resolutions. Models tend to underestimate tropical cyclones number especially over the Atlantic Ocean with horizontal resolution of the order of one degree (figure 1, central panel), with a substantial improvement moving to ¼ degree resolution (figure 1, lower panel), compared to the observations (figure 1, upper panel).

Only few models have demonstrated ability in generating a realistic distribution of tropical cyclone intensity within the five Saffir-Simpson hurricane classes (Wehner et al. 2014, 2015, Scoccimarro et al. 2017). Currently, there are only three GCMs worldwide able to represent category 5 TCs (Bathia et al. 2018). Coarse resolution (lower than 100 km) GCMs have only a limited ability to simulate tropical cyclone intensity, despite the reasonable performance in terms of interannual TC count variation (Zhao et al. 2009).

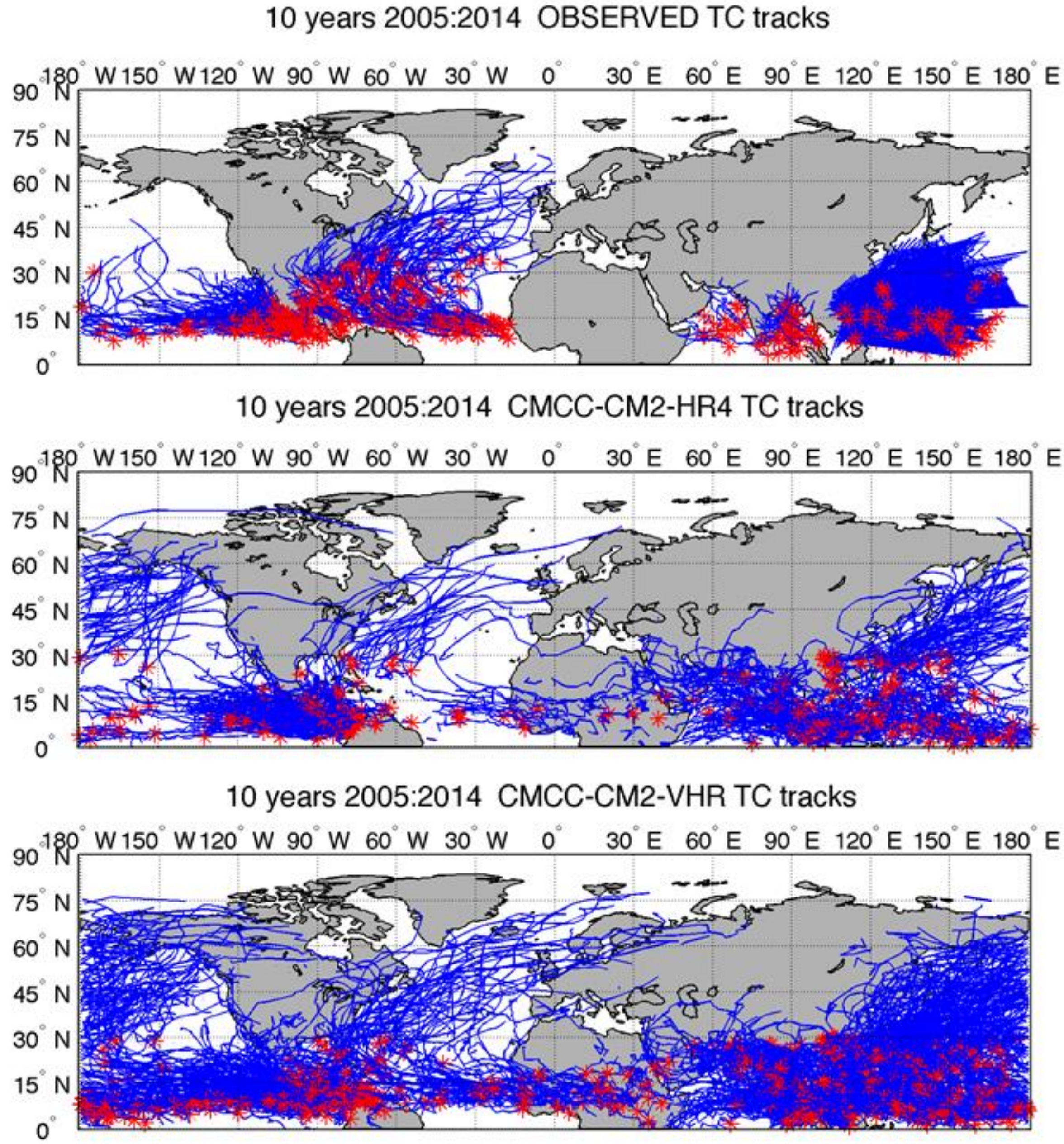

Figure 1: Observed Tropical Cyclone tracks in the 2005-2014 period (IBTrACS data) compared to 1 degree/0.25-degree (central/lower panels) CMCC-CM2 General Circulation Model results.

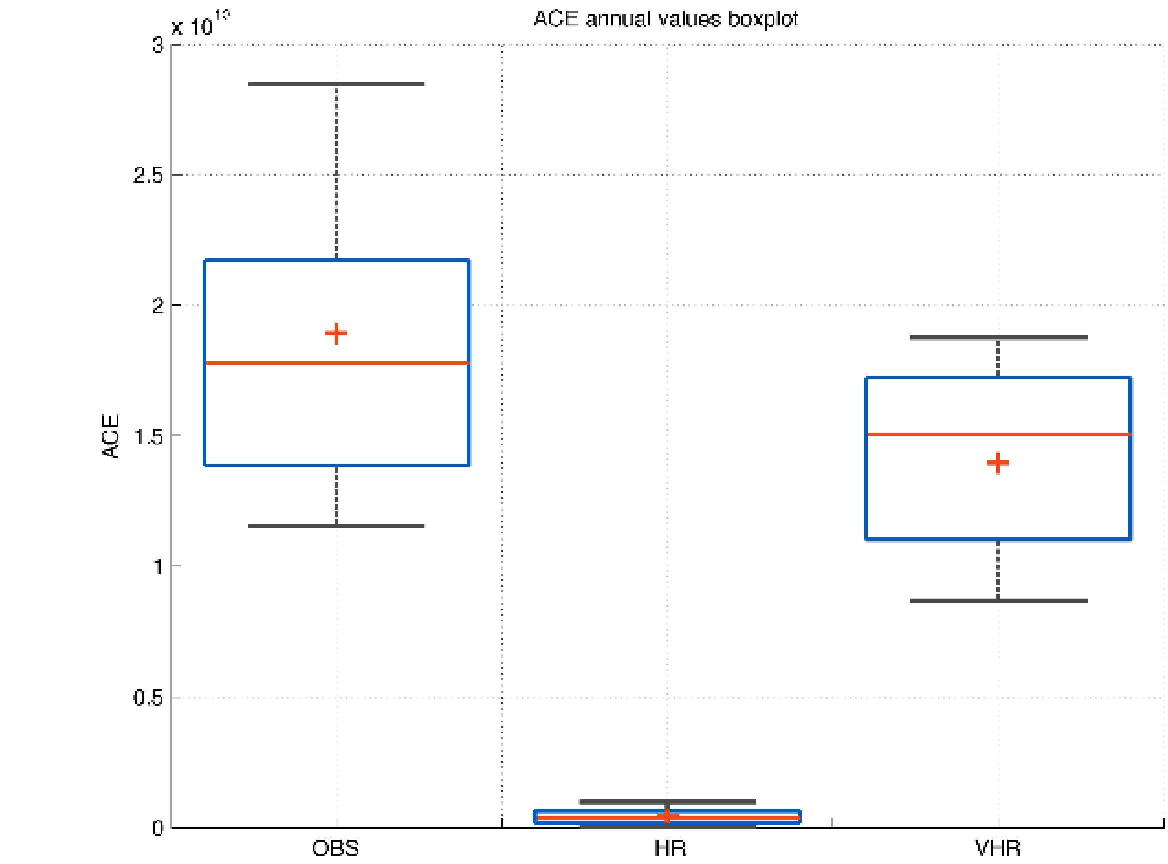

Figure 2: Observed Accumulated Cyclone Energy [m3s-2] over the West North Pacific in the 1979-2008 period compared to 1 degree/0.25-degree (central/right box) CMCC-CM2 fully coupled General Circulation Model results over the same domain. In each box plot, the box represents the interquartile range (IQR) and contains 50% of the data; the upper edge of the box represents the 75th percentile [upper quartile (UQ)], while the lower edge is the 25th percentile [lower quartile (LQ)]. The horizontal lines within the box are the median, and the "+" are the mean values.

As an example, Figure 2 highlights the deficiency of a coarse resolution (about 100 km) GCM in representing the Accumulated Cyclone Energy (ACE) by TCs in the West North Pacific compared to observations and higher resolution (about 25 km) modelling results. ACE is equal to the squared wind speed of each TC summed every 6 h and over all of the TCs active in a basin, over the considered period. It emerges that to obtain a realistic representation of the entire range of observed TC intensities a horizontal resolution of ¼ degree is necessary. In addition, the model horizontal resolution of ¼ degree highlights the importance of having a coupled ocean model to realistically represent the SST feedback, necessary to avoid too strong category 5 typhoons and hurricanes. This is evident in figure 3 where intense TCs are classified by categories in three different ¼ degree resolution CMCC-CM2 model configurations: an atmosphere only run (FORCED = black line), a coupled run with daily/hourly coupling between atmosphere and ocean components (LF/HF = red line/blue line). The overestimation of category 5 TCs is still present in the coupled simulation at the low coupling frequency (daily). The positive bias in strong TC classes, compared to the observations (black and red lines compared to the green line) disappears only when the hourly coupling between atmosphere and ocean is applied, linked to the realistic SST feedback representation.

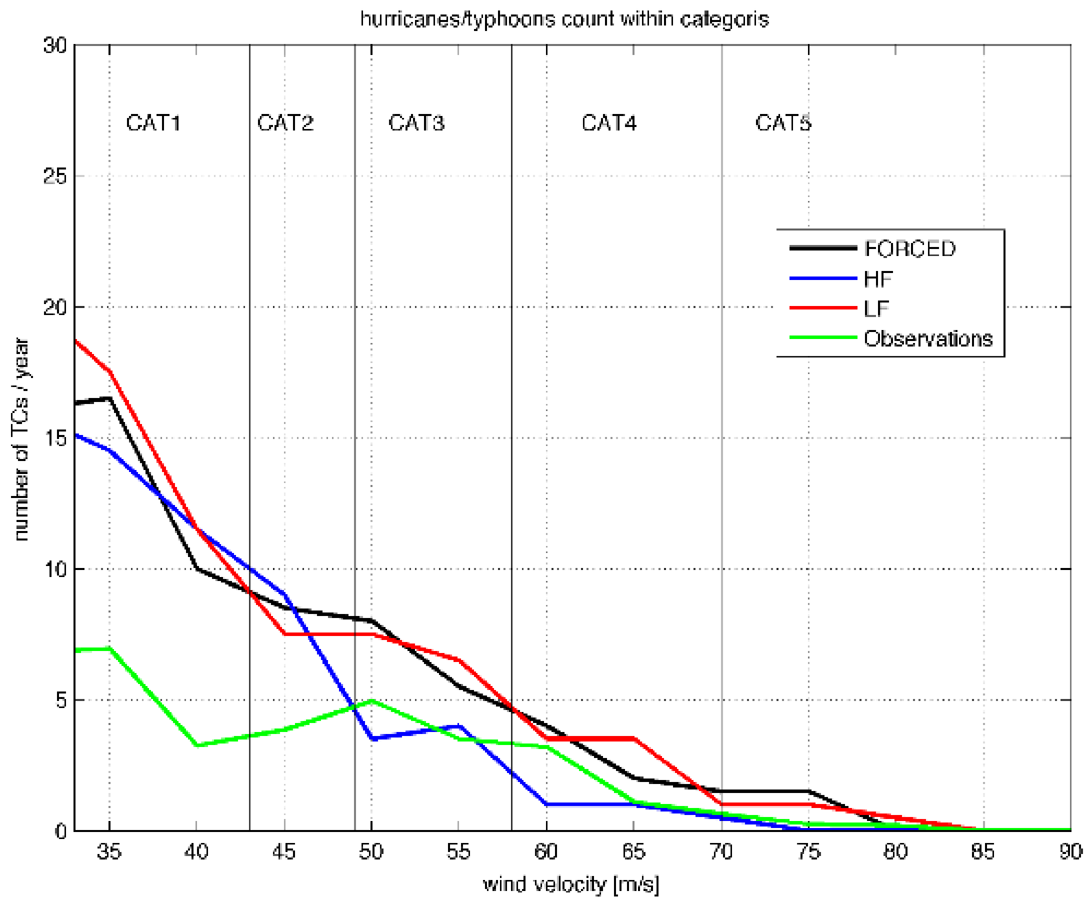

Figure 3: Hurricane/Typhoon representation in CMCC-CM2-VHR (0.25-degree horizontal resolution). FORCED (black) refers to an atmosphere only simulation. HF/LF (blue/red) refers to a coupled simulation with hourly/daily coupling between atmosphere and ocean components.

Prediction and Projection of Tropical Cyclone activity

Global scale dynamical models are used by many research centers around the world to forecast TC track and intensity on the short time scale (less than a week). These models take several hours to run on the most powerful supercomputers worldwide. On the other hand, a statistical approach, differently form the dynamical approach, does not explicitly consider the physics of the atmosphere but instead is based on historical relationships between storm behavior and storm-specific details such as averaged intensity or location. On a short time scale TC tracks and intensity forecast are performed through dynamical models, in association with statistical models and trajectory models.

Moving to the seasonal scale, predictions are mainly performed based on parameters indicative of the TC activity integrated over a basin (such as the ACE), without any consideration of TC track forecast, landfall estimate, etc. Dynamical downscaling has been shown to be a very useful tool also at the seasonal time scale and can be associated with a statistical approach (Vecchi and Villarini 2014). Different TC forecasting groups operate at the seasonal scale, mainly based on statistical approaches. A recent work also suggested that a significant step toward operationally reliable seasonal predictions of tropical cyclone activity in the Atlantic basin is gained after including upper ocean mean temperatures (upper 40-m averages) over the eastern Atlantic domain instead of surface temperature only, with remote effects providing potential skill up to 3 months in advance (Scoccimarro et al. 2018b).

A new source of information to the public relative to the hurricane seasonal forecast over the

Atlantic basin is offered by the BSC (Barcelona Supercomputing Center) Seasonal Hurricane Prediction group (http://seasonalhurricanepredictions.bsc.es/): the seasonal forecast of Accumulated Cyclone Energy provided by many (more than 20) forecast agencies (universities, private entities, government agencies) is collected and the averaged forecast is also shown in terms of normal, high or low forecasted activity, compared to the historical period.

Dynamical models are used not only for the prediction of TC activity at the short and medium-term time scales, but also to investigate TC activity under different future potential climate scenarios. A TC count reduction is expected in a warmer climate based on both fully coupled General Circulation Models and Hurricane model studies (Gualdi et al. 2008, Knutson et al. 2013): fewer TCs in a warmer climate are expected compared to the present climate, with a few exceptions (e.g., Emanuel, 2013) mainly due a less prone environment to the development of organized convective systems linked to a more stable projected atmospheric conditions . Such TC count reduction is mainly due to a reduction of the number of weak tropical storms and not to the most intense TCs. The strongest TCs, such as hurricanes and typhoons tend to be more frequent in a warmer climate as demonstrated based on dynamical downscaling of GCMs projections through hurricane models.

Another important aspect to investigate under different climate conditions is the TC associated precipitation, not used to define the “intensity” of a TC, but even more important for some impact evaluations. In terms of climate change effect on TC, there is consensus in claiming that an increase of associated rainfall amount is expected under warmer conditions (Gualdi et al. 2008; Knutson et al. 2013-2015; Villarini et al. 2014; Scoccimarro et al. 2014). The 10% to 20% projected increase has been associated with the enhanced tropospheric water vapour projected in a warmer climate, inducing an increase of the moisture convergence (Knutson et al. 2013-2015, Scoccimarro et al. 2014).

A strengthening of the coupling between dynamical and statistical prediction approaches is expected in the near future, together with the identification of new predictors that might emerge in a more realistic modelling framework. In addition, a more precise quantification of the TC fingerprint on the climate system will be obtained soon, thanks to the HighResMIP (Haarsma et al, 2016) data that will be made available within the upcoming 6th Coupled Model Intercomparison Project.

References

Bhatia, K. T., G. A. Vecchi, H. Murakami, S. Underwood, and J. Kossin,: Projected response of tropical cyclone intensity and intensification in a global climate model. *J. Climate*, **31**, 8281-8303. 2018.

Emanuel, K.A.: Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. Proc. Natl. Acad. Sci. USA, 110, 12219–12224, doi:10.1073/pnas.1301293110. 2013.

Gualdi, S., E. Scoccimarro, and A. Navarra: Changes in tropical cyclone activity due to global warming: Results from a high-resolution coupled general circulation model. J. Climate, 21, 5204–5228. 2008.

Haarsma, R. J., and Coauthors, 2016: High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6. Geosci. Model Dev., 9, 4185–4208, doi:10.5194/gmd-9-4185-2016.

Knutson T. R. et al.: Dynamical downscaling projections of 21st century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenario. Journal of Climate, 26(17), DOI:10.1175/JCLI-D-12-00539.1. 2013.

Knutson T. R. et al.: Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios. Journal of Climate, 28(18), DOI:10.1175/JCLI-D-15-0129.1. 2015.

Scoccimarro E. et al.: Effects of Tropical Cyclones on Ocean Heat Transport in a High-Resolution Coupled General Circulation Model. J. Climate, 24, 4368–4384. 2011.

Scoccimarro E., S. Gualdi, A. Navarra: Tropical Cyclone Effects on Arctic Sea Ice Variability. Geophysical Research Letters, 39, L17704, doi:10.1029/2012GL052987. 2012.

Scoccimarro, E., S. Gualdi, G. Villarini, G. Vecchi, M. Zhao, K. Walsh, and A. Navarra: Intense precipitation events associated with landfalling tropical cyclones in response to a warmer climate and increased CO2. J. Climate, 27, 4642-4654. 2014.

Scoccimarro E.: Modelling Tropical Cyclones in a changing climate. “Oxford Research Encyclopedia of Natural Hazard Science”. Oxford University Press. DOI:10.1093/acrefore/9780199389407.013.22. 2016.

Scoccimarro E., P.G. Fogli. K. Reed, S. Gualdi, S.Masina, A. Navarra: Tropical cyclone interaction with the ocean: the role of high frequency (sub-daily) coupled processes. 2017. *Journal of Climate*, doi: 10.1175/JCLI-D-16-0292.1

Scoccimarro E., S. Gualdi, S.O. Krichack: Extreme precipitation events over north-western Europe: getting water from the tropics. *Annals of Geophysics*, doi: 10.4401/ag-7772. 2018a.

Scoccimarro E., Bellucci A., Storto A., Gualdi S., MAsina S., Navarra A.: Remote sub-surface ocean temperature as a predictor of Atlantic hurricane activity. PNAS doi:10.1073/pnas.1810755115. 2018b.

Vecchi G.A. and G. Villarini: Next season’s hurricanes. Science, 343, 618–619, doi:10.1126/science.1247759. 2014.

Villarini G., Goska R., Smith J.A., Vecchi G.A.: North Atlantic tropical cyclones and U.S. flooding. Bull Am Meteorol Soc. 95:1381–1388, 2014.

Wehner, M. F et al., Resolution dependence of future tropical cyclone projections of CAM5.1 in the U.S. CLIVAR Hurricane Working Group idealized configurations, J. Clim., doi:10.1175/JCLI-D-14-00311.1, 2015.

Wehner, M. F., et al., The effect of horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1, J. Adv. Model. Earth Syst., 6, 980–997, doi:10.1002/2013MS000276, 2014.

Zhao, M., I. M. Held, S.-J. Lin, and G. A. Vecchi: Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50km resolution GCM. J. Climate, 22, 6653–6678. 2009.