Supplementary Information: TSR Forecast Methodology

Contents

1. Definitions
2. TSR forecast Methodology
    a) Primary Model
        i) North Atlantic model
        ii) NW Pacific models
    b) Procedures, Checks and Adjustments to Finalise Forecast
3. Forecast Probability of Exceedance Plots
4. Precision of TSR Seasonal Hurricane Forecasts 2003-2022 Issued Publicly
5. Acknowledgements
6. References

1. Definitions

ACE Index	=	Accumulated Cyclone Energy Index = Sum of the squares of 6-hourly maximum sustained wind speeds (in units of knots) for all systems while they are at least tropical storm strength. ACE unit = $x10^4$ $knots^2$.
Intense Hurricane	=	1 minute sustained wind > 95 kts = Hurricane category 3 to 5.
Hurricane	=	1 minute sustained wind > 63 kts = Hurricane category 1 to 5.
Tropical Storm	=	1 minute sustained wind > 33 kts.
Forecast Skill	=	Percentage improvement in mean square error over running 10-year prior climate norm for the TSR publicly-released seasonal outlooks for the 20-years 2003-2022.
Terciles	=	Data groupings of equal (33.3%) probability corresponding to the upper, middle and lower one-third of values for the current 30-year climate norm (1991-2020). Tercile values (1991-2020 climate norm) for total Atlantic activity are: Upper tercile = 156; lower tercile = 75; for the US ACE index: Upper tercile = 3.19; lower tercile = 1.18.
US ACE Index	=	Accumulated Cyclone Energy Index = Sum of the Squares of h hourly Maximum Sustained Wind Speeds (in units of knots) for all Systems while they are at least Tropical Storm Strength and over the USA Mainland (reduced by a factor of 6). ACE Unit = x 10^4 $knots^2$.
Strike Category	=	Maximum 1 Minute Sustained Wind of Storm Directly Striking Land.
USA Mainland	=	Brownsville (Texas) to Maine.

2. TSR Forecast Methodology

a) Primary Models

The TSR forecast models are statistical in nature and are underpinned by predictors that have sound physical links to contemporaneous TC activity. The methodoogy behind the North Atlantic and NW Pacific models are described in sub-sections i) (Atlantic) and ii) (Pacific) below.

i) North Atlantic Primary Model

The TSR primary model first divides the North Atlantic basin into three regions: (1) the tropical North Atlantic; (2) the Caribbean Sea and Gulf of Mexico; and (3) the 'rest' region which comprises the North Atlantic area outside regions (1) and (2). The TSR primary model then employs separate forecast models for each of the three regions before summing the regional hurricane forecasts to obtain an overall North Atlantic hurricane forecast.

The two main predictors used by the TSR primary model in making its seasonal North Atlantic hurricane forecasts are:

Predictor 1: The forecast speed of the trade winds for July-August-September for the region 7.5-17.5°N, 100-30°W. The trade winds blow westward across the tropical Atlantic and Caribbean Sea and influence cyclonic vorticity and vertical wind shear over the main hurricane track region.

Predictor 2: The forecast sea surface temperature (SST) for August-September for the region 10-20°N, 60-20°W between west Africa and the Caribbean where many TCs develop during August and September. Waters here provide heat and moisture to help power the development of storms within the hurricane main development region.

Predictor 1 is forecast at this lead time using persistence from July trade wind anomalies for the region 7.5-17.5°N, 100-30°W. Tropical Atlantic SSTs are forecast using a statistical principal component model which, at each forecast lead, employs the 1-month lagged principal component of the leading mode of north Atlantic SST variability for the region 0°N-50°N, 0°W-100°W (Pacific Ocean excluded).

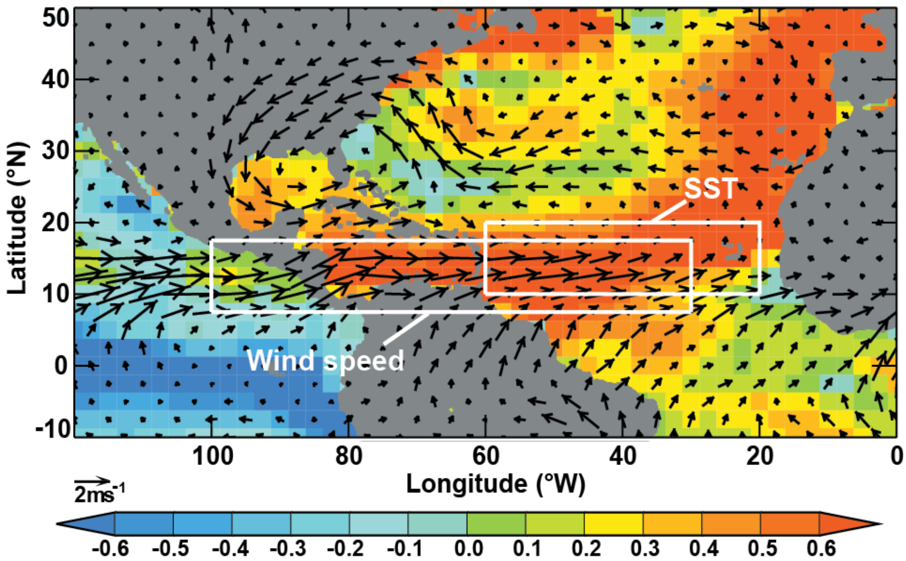

Figure 2. Nature of the TSR statistical model for replicating North Atlantic seasonal hurricane activity. The figure displays the two August-September environmental field areas that the TSR model employs most often in producing a seasonal hurricane outlook. The figure also displays the anomalies in August-September SST (colour coded in °C) and 925 hPa wind (arrowed) linked to active Atlantic hurricane years. Figure taken from Saunders and Lea (2008).

The nature of the TSR primary model is shown in Figure 2 and is described further in Lea and Saunders (2004, 2006), Saunders (2006) and Saunders and Lea (2008). The basis for the trade wind speed being the environmental field that best replicates long-term hurricane activity for the period 1878-2012 is given in Saunders et al. (2017). The methodology of the TSR primary seasonal forecast models is also documented in the recent reviews on seasonal tropical cyclone forecasting by Klotzbach et al. (2017, 2019).

TSR forecasts for US landfalling TC activity issued between December and July employ a historical thinning factor between 'tropical' North Atlantic activity and US landfalling activity. The TSR forecast for US landfalling activity issued in early August employs the persistence of July steering winds (Saunders and Lea, 2005). These winds either favour or hinder evolving hurricanes from reaching US shores during August and September. The replicated real-time correlation skill for predicting the US ACE Index from early August assessed for the 43-year period 1980-2022 is $r = 0.54$.

All regressions are performed using normalized data for all variables (predictands and predictors). This ensures that the requirements of linear regression modeling are met; namely that observations are drawn from normal distributions and that regression errors are normally distributed with a mean of zero. In each case the transform distribution is determined using 1950-2019 data. Table S2 in Supporting Information in Saunders et al (2020) lists some of the statistical distributions used to transform particular data sets to a normalized distribution. Normality is assessed using the Anderson-Darling statistical test.

ii) NW Pacific Primary Models

The TSR primary models are underpinned by the expected state of El Niño Southern Oscillation (ENSO) in August-September-October (ASO). Figure 2 shows the strong linear link that exists between the magnitude of the annual Northwest Pacific ACE index and the sign and magnitude of the ASO ENSO (see also, for example, Saunders et al. (2000) and Maue (2011)). ENSO is represented in Figure 1 by the Oceanic Niño Index (ONI) defined as the 3-month average surface temperature anomaly for the Nino 3.4 region. When the ASO ENSO ONI value is ≤ -1 the ACE index is 200 or less. In contrast, when the ASO ENSO ONI is ≥ 1 the ACE index is 400 or more.

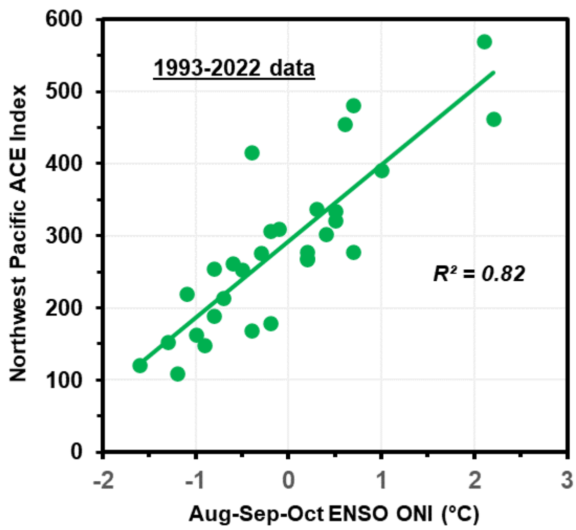

Figure 1. Nature of the TSR primary model for forecasting Northwest Pacific seasonal typhoon activity. The figure shows the strong linear link ($R^2 = 0.82$; 1993-2022) between the annual Northwest Pacific ACE index and the sign and magnitude of ENSO in August-September-October.

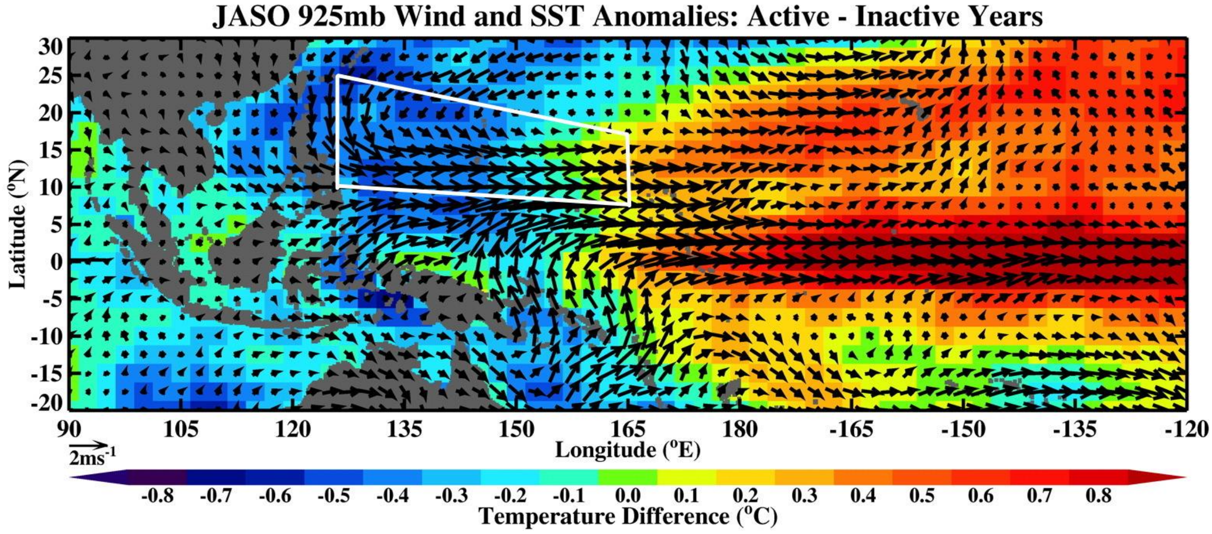

Figure 2. Nature of the physical mechanism behind the TSR primary model in Figure 1. The composite difference figure shows the dominant July-August-September-October (JASO) environmental fields associated with active Northwest Pacific intense typhoon years. Active typhoon seasons occur due to the effects of the anomalous Walker circulation and the resulting weakened easterly trade winds that occur over the tropical Northwest Pacific due to El Niño (warm ENSO) conditions. Inactive typhoon seasons occur due to the effects of the anomalous Walker circulation and the resulting strengthened easterly trade winds that occur over the tropical Northwest Pacific due to La Niña (cold ENSO) conditions. The white quadrilateral denotes where Northwest Pacific tropical cyclones become intense typhoons.

The physical mechanism behind the strong ASO ENSO link to Northwest Pacific seasonal ACE and seasonal intense typhoon numbers is described in Lea and Saunders (2006) and is illustrated in Figure 3. When ASO ENSO is El Niño (ONI value > 0.5°C) the anomalous Walker circulation leads to anomalously weak trade winds in the Northwest Pacific between 2.5°N and 12.5°N. These in turn increase the cyclonic vorticity and decrease the vertical wind shear where intense typhoons form and track, leading to greater intense typhoon numbers and to an enhanced seasonal ACE index. In contrast when ASO ENSO is La Niña (ONI value < -0.5°C) the anomalous Walker circulation leads to anomalously strong trade winds in the Northwest Pacific between 2.5°N and 12.5°N. These in turn weaken the cyclonic vorticity and increase the vertical wind shear where intense typhoons form and track, leading to fewer intense typhoon numbers and to a reduced seasonal ACE index.

The predictor(s) used for each TSR seasonal forecast primary model are as follows:

Early May: ACE is forecast from our expectation for the value for ASO ENSO ONI and the regression in Figure 2. Intense typhoon numbers are forecast by using their observed regression with ACE for 1998-2022. Typhoon numbers are forecast by using their observed regression with intense typhoon numbers for 1998-2022. Tropical storm numbers are forecast by using their observed regression with typhoon numbers for 1991-2022.

Early July: ACE is forecast from our expectation for the value for ASO ENSO ONI, using the June 925 hPa trade wind speed for the region 2.5°N-12.5°N, 120°E-180°E and by using the observed ACE activity up to the date of the forecast issue. Storm numbers are forecast by applying the methods used in the early May forecast.

Early August: ACE and intense typhoon numbers are forecast by using the June-July 925 hPa trade wind speed for the region 2.5°N-12.5°N, 120°E-180°E and by using the observed ACE activity up to the date of the forecast issue. Typhoon numbers and tropical storm numbers are forecast by using their observed regression with intense typhoon numbers.

The ASO ENSO is predicted by using the statistical consolidated CLIPER model (Lloyd-Hughes, Saunders and Rockett, 2004) and by the methods described in §2b.

All regressions are performed using normalized data for all variables (predictands and predictors). This ensures that the requirements of linear regression modeling are met; namely that observations are drawn from normal distributions and that regression errors are normally distributed with a mean of zero. Table S2 in Supporting Information in Saunders et al (2020) lists some of the statistical distributions used to transform particular data sets to a normalized distribution. Normality is assessed using the Anderson-Darling statistical test.

b) Procedures, Checks and Adjustments to Finalise Forecast:

Each TSR seasonal hurricane forecast is initiated by running the TSR primary seasonal forecast model with NCEP/NCAR reanalysis data updated to within a few days of the seasonal forecast issue date. The output from this primary model is then assessed in combination with several other sources of information before the final values for the seasonal forecast are decided. These other sources of information often lead either to the TSR primary forecast model bring rerun with different values for its two main predictors or to the outputs of the primary models being manually adjusted.

The sources of other information that are referred to when finalising the TSR North Atlantic seasonal hurricane forecasts include the following:

- ENSO consensus forecasts compiled and provided by IRI (International Research Institute for Climate and Society).
- NCEP CFSv2 seasonal forecast data (updated daily).
- ECMWF seasonal forecast data (updated monthly).
- NOAA 'ENSO: recent evolution, current status and predictions' weekly report.
- UCL unpublished 'statistical composite prediction of ENSO outcomes' data.
- Tropical Tidbits data and forecast data (updated daily).
- North Atlantic Oscillation (NAO) CPC forecast data and monthly index data (updated twice daily).
- Atlantic Multidecadal Oscillation (AMO) index data (updated monthly).
- Atlantic Meridional Mode (AMM) SST index data (updated monthly).
- UCL unpublished data showing the strength, significance and timing of NAO, ENSO, AMO and AMM seasonal links to upcoming North Atlantic hurricane activity.

The following procedures and adjustments to the outputs from the TSR primary forecast model are made in order to enhance forecast precision:

a) The additional information sources are used to give consensus values for the TSR two underpinning primary predictor values (Aug-Sep Nino 3.4 SST and Aug-Sep MDR SST). In determining the consensus value for each predictor more weight is given to forecasts from the *NCEP CFSv2* and *ECMWF* models and from the *UCL "Statistical composite prediction of ENSO outcomes".*

b) If the consensus values obtained from (a) for either primary predictor (§2.1) differ by more than 0.1°C from the values output by the TSR primary forecast model then the TSR primary model is rerun with the consensus values for each SST predictor to give a revised seasonal hurricane forecast.

c) If $ENSO_{AMJ}$ is neutral and either NAO_{AMJ} or AMO_{AMJ} is anticipated to lie in either the upper or lower quartile of historical values then a separate regression forecast for North Atlantic hurricane activity is made using either NAO_{AMJ} or AMO_{AMJ} as the sole predictor. This forecast is then used in parallel with the primary model forecast (or the latter is adjusted based on the former).

d) If either AMM_{JJA} or AMM_{JAS} is anticipated to be in the upper or lower quartile then allowance is made for this when finalizing the North Atlantic seasonal hurricane forecast.

e) If forecasts anticipate the intensification of either a La Niña or an El Niño event during the second half of the hurricane/typhoon season (namely during the period from mid September to the end of November) the TSR seasonal hurricane forecasts (especially the early July and early August forecasts) are adjusted slightly to reflect this ENSO intensification.

3. Forecast Probability of Exceedance Plots

Seasonal outlooks for North Atlantic hurricane activity and NW Pacific typhoon activity contribute to the anticipation of risk for insurance companies, other weather-sensitive businesses, and local and national governments. However, the uncertainty associated with such forecasts is often unclear. This reduces their benefit and contributes to the perception of forecast 'busts'. The robust assessment of risk requires a full and clear probabilistic quantification of forecast uncertainty with the forecast issued in terms of probability of exceedance (PoE). In this way the chance of each hurricane number/activity outcome occurring is clear for the benefit of users. Going forward TSR will be including robust forecast probability of exceedance (PoE) information based on the recommendation and methodology described in Saunders et al. (2020)

4. Precision of TSR Seasonal Hurricane Forecasts 2003-2022 Issued Publicly

a) North Atlantic

Figure 3 displays the seasonal forecast skill for North Atlantic hurricane activity for the 20-year period between 2003 and 2022. This skill assessment uses the seasonal forecast values that were issued publicly in real-time by the three forecast centres TSR, CSU (Colorado State University) and NOAA (National Oceanic and Atmospheric Administration). Skill is displayed as a function of lead time for two measures of seasonal hurricane activity: the ACE index and basin hurricane numbers.

The Mean Square Skill Score (MSSS) is used to define the forecast skill. MSSS is the percentage improvement in mean square error over a climatology forecast. Positive skill indicates that the model performs better than climatology, while a negative skill indicates that it performs worse than climatology. Two different climatologies are used: a fixed 50-year (1951-2000) climatology and a running prior 10-year climate norm.

It should be noted that NOAA does not issue seasonal hurricane outlooks before late May and that CSU stopped providing quantitative extended-range hurricane outlooks from the prior December after 2011. It is clear there is little skill in forecasting the upcoming ACE and numbers of hurricanes from the previous December for the period 2003-2022. Skill starts to climb after April as the hurricane season approaches with moderate-to-good skill levels being achieved, on average, by early August.

Although there are mostly only small differences in skill between the three forecast centres, the TSR model has been either the near-equal best or the best performing statistical seasonal forecast model at all lead times for the period 2003-2022.

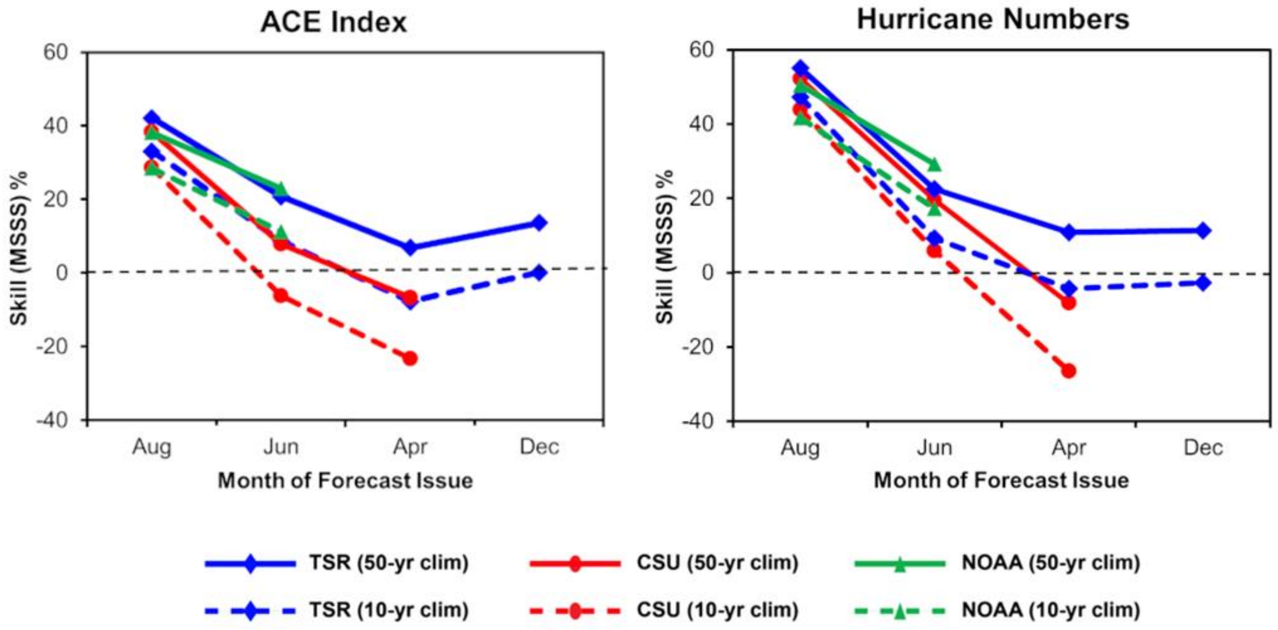

Figure 3. Real-time skill of North Atlantic seasonal tropical cyclone outlooks assessed for the 20-year period 2003-2022. The skill of the seasonal outlooks issued publicly by Tropical Storm Risk (TSR, blue lines), Colorado State University (CSU, red lines), and the National Oceanic and Atmospheric Administration (NOAA, green lines) are compared for ACE (left panel) and for hurricane numbers (right panel). The skill is shown as the Mean Square Skill Score (MSSS) based on a fixed 50-year (1951-2000) climatology and on a running prior 10-year climate norm.

b) NW Pacific

The skill of the TSR seasonal forecasts for Northwest Pacific typhoon activity issued publicly in real-time for the 16-year period 2003-2018 were assessed by Klotzbach et al (2019) (see their Figure 4). Figure 4 extends the Klotzbach et al. skill assessment to span the period between 2003 and 2022. Skill is displayed as a function of forecast lead-time for two measures of seasonal typhoon activity – the basin ACE index and basin intense typhoon numbers. Figure 4 shows that the TSR seasonal forecast skill from early May is low. However, the TSR skill climbs during May and June to reach moderate-to-good levels (r = 0.45 to 0.80) by early July. The correlation skill for typhoon numbers (not shown) is lower, reaching 0.39 by early August.

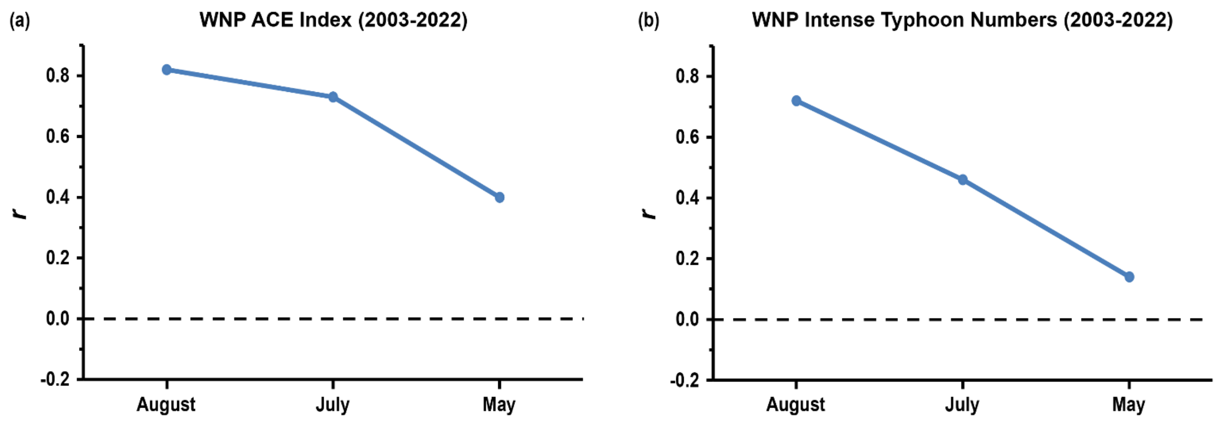

Figure 4. Real-time skill of the TSR seasonal outlooks for northwest Pacific (a) ACE and (b) intense typhoon numbers assessed for the 20-year period 2003-2022. Skill is shown as the

Pearson correlation, *r*, between the forecast values (issued separately in early May, early July and early August) and the observed values.

5. Acknowledgements:

The TSR (Tropical Storm Risk) North Atlantic (NW Pacific) seasonal hurricane forecasts were instigated in 1998 (2000) by Professor Mark Saunders at UCL with funding from the UK insurance industry. Saunders led these predictions until his retirement in April 2022. Notable contributions to the development and operation of the TSR seasonal hurricane forecasts were made also by the following scientists (all former UCL research assistants of Saunders): Professor Chris Merchant, Dr Paul Rockett, Dr Adam Lea and Frank Roberts.

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