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Seasonal forecasting of tropical storm frequency

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Seasonal forecasting of tropical storm frequency

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Tropical storms (tropical cyclones with a maximum wind speed larger than 17 m s^{-1}) give rise to some of the most devastating natural disasters. During the past 50 years, hundred of thousands of lives have been lost because of tropical storm landfalls, often because of the landslides and floods caused by the heavy precipitations associated to the storm. The total number of tropical storms is remarkably stable from one year to another (about 90 per year), but their frequency can vary strongly from one year to another over a specific ocean basin. For instance, only 3 Atlantic tropical storms were observed in 1983, compared to 27 in 2005. As a consequence the damage caused by tropical storms, especially by the most intense ones (hurricanes or typhoons), can vary significantly from one season to another. Therefore making accurate seasonal forecasts of tropical storm frequency is a very valuable tool to help people prepare for such disasters. Predicting their exact occurrence months in advance is of course out of reach, but predicting their probability of occurrence may be possible.

As tropical storms form in very specific locations and are highly seasonal; specific environmental conditions are required to accomplish the transition from a loosely organized disturbance to an intense vortex. *Gray* (1979) identified six main environmental factors related to the frequency of tropical cyclones:

- Above average low-level vorticity.
- A location a few degree poleward of the equator (the Coriolis force plays an important role in the generation of cyclones).
- Weak vertical shear of the horizontal wind.
- Sea surface temperature exceeding 26°C.
- Conditional instability through a deep layer in the atmosphere.
- Above-average moisture in the middle levels of the atmosphere.

Those parameters, which are not independent, can explain the seasonal cycle of tropical cyclone activity and why tropical storms form only in specific regions. They can also explain changes in the frequency of tropical cyclones from one year to another. For instance the Atlantic tropical cyclone activity is significantly reduced during El Niño years. The proposed mechanism is that the eastward shift of positive sea-surface temperature anomalies associated with El Niño causes an increase of deep convection over the Equatorial Eastern Pacific. This increased convection enhances the upper-level westerly zonal winds and, as a consequence, the vertical wind shear over the region where most Atlantic tropical storms develop. As discussed previously, the increased vertical wind shear reduces the Atlantic tropical storm activity.

Tropical storms in the ECMWF seasonal forecasting system

At present most seasonal forecasts of tropical cyclone activity (forecasts from Colorado State University, NOAA or Tropical Storm Risk Consortium) are produced using statistical or empirical methods. An alternative to those methods is the use of dynamical models that have skill in predicting a few months in advance the large-scale parameters that have an impact on the frequency of tropical storms.

The current operational version of the ECMWF seasonal forecasting system, System 3, is described in *Anderson et al.* (2007) and its products in *Molteni et al.* (2007). This system has some skill in predicting the evolution of sea surface temperatures (SSTs) a few months in advance in the tropics, most especially the SST anomalies associated with ENSO in the tropical Pacific. Therefore, this system could be used for the prediction of tropical storms by building a simple statistical model based on the predicted SSTs: for instance, if the coupled model predicts colder Atlantic SST and an El Niño event during the peak of the Atlantic tropical storm season (August-September-October), then it is likely that the Atlantic tropical storm season will be inactive. Another method consists of counting the “tropical storms” produced explicitly by the dynamical model. This is the method we use to produce the ECMWF seasonal forecasts of tropical storms. It has the advantage over the statistical method of a better handling of non-linear effects on tropical storm frequency and of allowing the explicit representation of tropical storm tracks.

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Although the horizontal resolution of global operational dynamical seasonal forecasting models is insufficient to simulate the intensity of hurricanes, simulated tropical cyclonic systems are nevertheless realistic in other respects. For example, the number of dynamically-simulated Atlantic tropical storms developed over the course of a season is sensitive to the underlying SSTs (*Vitart & Anderson,* 2001). In addition, dynamically-simulated tropical storms develop a warm temperature anomaly above the centre of the vortex (warm core). This warm-core structure is crucial to the intensification of tropical storms, and plays an important role in understanding the inter-annual variability of observed tropical storms: an increase in vertical wind shear prevents the formation of a warm core structure. Numerical experiments have shown that this mechanism can be simulated in dynamical models (*Vitart & Anderson,* 2001). These results form the scientific basis for dynamically-based seasonal forecasting of tropical storms.

Seasonal forecasts of tropical storms have been issued each month since 2001 at ECMWF. The seasonal forecast of tropical storm frequency (see example in Figure 1) and the mean genesis location (see example in Figure 2) are displayed on the ECMWF web site. Because of the seasonality of tropical storms, forecasts over the North Atlantic, Eastern North Pacific and Western North Pacific are issued only from March to August, and forecasts over the southern hemisphere are issued only from September to February. The first month of the forecast is excluded since the forecasts are issued on the 15th of the first month. Since April 2007, the forecasts are produced using ECMWF System 3 instead of ECMWF System 2. The products are available to ECMWF Member States and WMO users.

The forecasts are produced by tracking the tropical storms in the atmospheric component of the ECMWF seasonal forecasting system. The number of model tropical storms is counted over each basin. Dynamical models tend to drift towards a climate that is different from the observed climate. The effect of the drift on the model calculations is estimated from integrations of the model for previous years (the re-forecast). The drift is then removed from the model solution *a posteriori* (the calibration). For most model variables, including sea-surface temperature, the drift is treated as a bias and removed additively. For tropical storm numbers, the model climate can differ substantially from the observed climate. In this case, we calibrate the number of tropical storms in a given year by considering it relative to the central distribution of the climate; that is we multiply the number of model storms by a factor such that the central distribution of the model climate equals the central distribution of the observed climate. It would be possible to estimate both a mean offset and a correction of the model variance independently. However, this introduces an additional degree of freedom which is undesirable in such a small dataset.

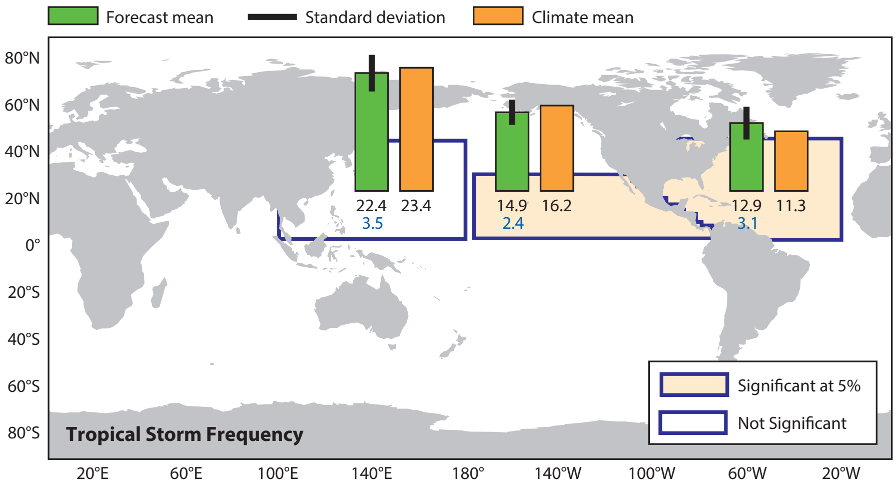

Figure 1 Frequency of model tropical storms. The 41-member ensemble forecast starting on 1 May 2007 for June to October is compared with the climatology for 1981–2005. A Wilcoxon-Mann-Whitney (WMW) test is then applied to evaluate if the predicted tropical storm frequency is significantly different from the climatology. The ocean basins where the WMW test detects a significance larger than 90% have a shaded background. Green bars represent the ensemble mean of the forecast and orange bars represent climatology. The values of each bar are written in black. The black bars represent ±1 standard deviation within the ensemble distribution, these values are indicated by the blue numbers.

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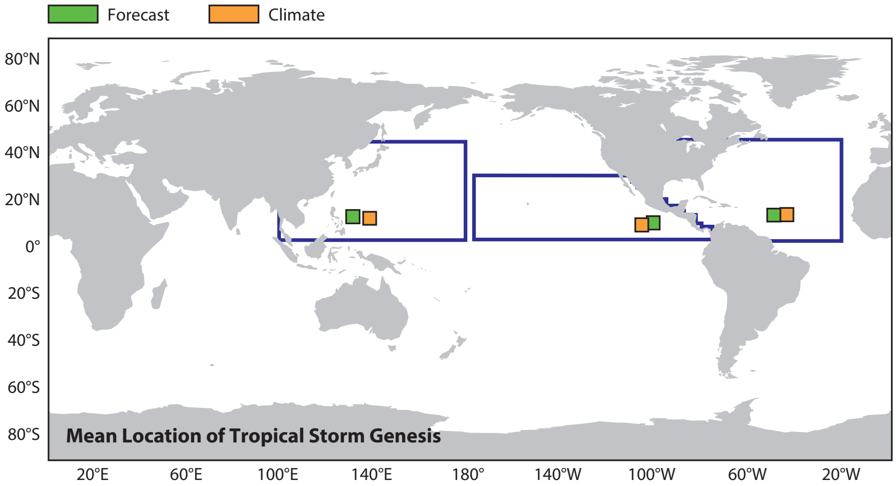

Figure 2 Mean genesis locations of model tropical storms. The green square represents the mean location from the ensemble forecast starting on 1 May 2007 for June to October, and the orange square the mean genesis location from the model climate for 1981–2005.

Tropical storm detection

A major problem when tracking storms from model forecasts and analyses consists of detecting as many tropical storms as possible without detecting extra-tropical storms or weak tropical depressions that have a different inter-annual variability. Therefore, the criteria for detecting a model tropical storm have been chosen to be harsh enough so that, when applied to ECMWF analyses projected on the same low resolution as the dynamical model outputs, almost all systems detected correspond to observed tropical storms. The algorithm to detect the simulated tropical storms is the following.

1.1 A local maximum of vorticity more than 3.5×10^{-5} s^{-1} at 850 hPa is located and the closest minimum sea level pressure is defined as the centre of the storm.

1.2 The closest local maximum of averaged temperature between 500 and 200 hPa is located and is defined as the centre of the warm core. The distance between the centre of the warm core and the centre of the storm must not exceed 2° latitude. From the centre of the warm core the temperature must decrease by at least 0.5°C in all directions within a distance of 8° latitude.

1.3 The closest local maximum thickness between 1000 and 200 hPa is located. The distance between this local maximum and the centre of the storm must not exceed 2° latitude. From this local maximum, the thickness must decrease by at least 50 m in all directions within a distance of 8° latitude.

To locate the position of the centre with a higher precision than the model resolution, bicubic splines interpolate the fields from the grid-point values and then a conjugate gradient algorithm locates the position of a maximum or a minimum of the fields. After the storms are located for each day, the following objective procedure is applied to find storm trajectories.

2.1 For a given storm, it is determined whether there are storms that appear on the following day at a distance of less than a maximum distance which depends on the model resolution.

2.2 If there is no such storm, the trajectory is considered to have stopped. If there is more than one storm, a preference is given to a westward and poleward trajectory since the majority of tropical storms move in that direction.

2.3 To be considered a tropical storm trajectory, a trajectory must last at least two days, and have a maximum wind velocity within an 8o circle centred in the middle of the storm, which must be larger than a certain threshold at 850 hPa. The threshold is dependent on the model resolution.

Cases satisfying these criteria are referred to as model tropical storms. In order to get longer trajectories that include the phase when the tropical storm is a tropical depression, criteria 1.2, 1.3 and 2.3 need to be verified only during two days.

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Comparison of results from System 2 and System 3

Tropical cyclone tracks

Tropical storms have been tracked in the ECMWF seasonal forecasting system using the algorithm described above. The model tropical storms appear in the same regions as those observed. As in observations, there are no model tropical storms in the South East Pacific and they are very rare in the South Atlantic.

The realism of the model tropical storm tracks is strongly related to the resolution of the atmospheric model and there has been a clear improvement in the realism of the model tropical storm tracks between System 2 with a T95 resolution and System 3 which has a higher horizontal resolution of T159. Figure 3 gives an example of some cyclone trajectories produced by System 2 and System 3.

Frequency of model tropical storms

Figure 4 shows the mean number of tropical storms per year during the period 1987–2004 over each ocean basin obtained with Systems 2 and 3, along with the observed annual frequency from operational centres such as the National Hurricane Center (NHC). System 2, which has a coarser resolution than System 3, produces globally about half the number of observed tropical storms. On the other hand System 3 has a more realistic climatology with about 80 tropical storms per year globally compared to 90 observed tropical storms. However, System 3 still underestimates strongly the number of tropical storms over the Eastern North Pacific, although the deficit in this basin is smaller than in System 2.

Seasonal variability

The number of model tropical storms has been calculated for each month. Over the North Atlantic the ECMWF seasonal forecasting system has a peak activity in August-September-October as observed (Figure 5). However, the model has too many Atlantic tropical storms at the beginning of the season and too few during the peak season. Over the Eastern and Western North Pacific basins, the model tropical storms occur at the same time as those observed, but the peak period is one month too late. Over the southern hemisphere the model simulates storms from September to April as observed. The North Indian Ocean is the only basin where the model seasonal cycle is badly wrong. There are two tropical cyclone seasons over the Indian Ocean: from April to June and from September to December. The model tropical storms display only one season over the North Indian Ocean, which peaks in July and August. This is probably because monsoons troughs are wrongly identified as tropical cyclones. For this reason, seasonal forecast of tropical storms over the North Indian Ocean are not issued.

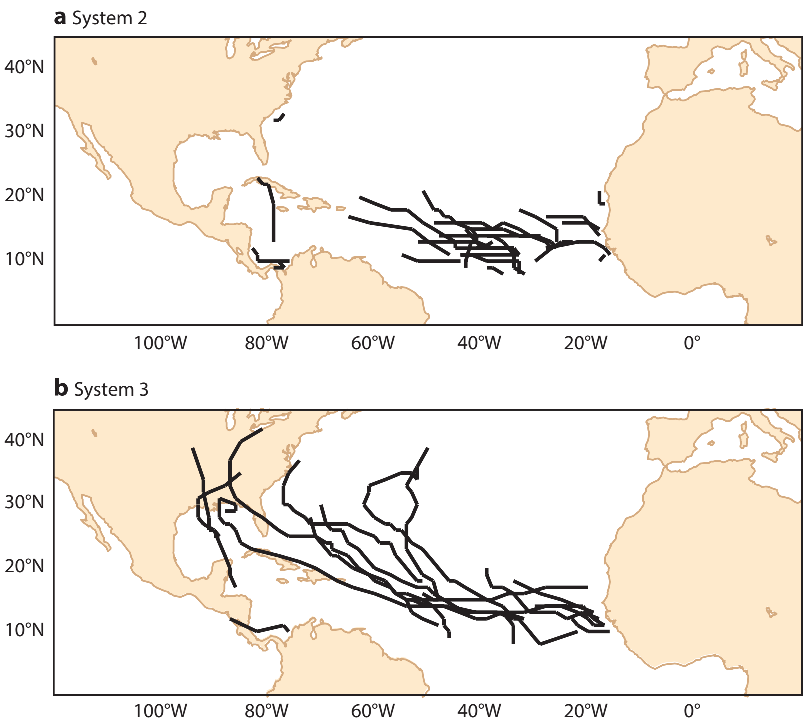

Figure 3 An example of an ensemble of trajectories in (a) System 2 and (b) System 3. The tracks are produced by forecasts starting on 1 June 2000. For reason of clarity just three ensemble members are shown.

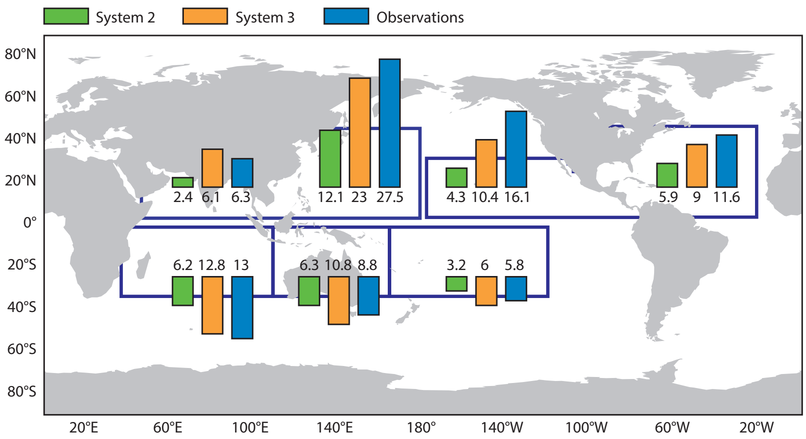

Figure 4 Number of tropical storms per year over the period 1987–2004. The green bars represent the number of tropical storms simulated by System 2. The orange bars represent the number of tropical storms simulated by System 3. The blue bars represent the observed frequency.

Calibration factor

As discussed above, the number of tropical storms predicted by the seasonal forecasting system is calibrated a posteriori by multiplying it by a factor such that the central distribution of the model climate equals the central distribution of the observed climate. Table 1 shows the calibration factors applied with System 2 and System 3 for the forecasts starting on 1 June over the northern hemisphere and 1 October over the southern hemisphere. With System 3, the calibration factors are closer to 1 than with System 2 confirming that the tropical storm climatology is more realistic with System 3 than with System 2. With System 3 the coefficients are indeed very close to 1 in the southern hemisphere. Over the northern hemisphere they are still larger than 1 indicating that the seasonal forecasting System 3 produces too few tropical storms over the period July–October (as can be seen in Figure 5 for the North Atlantic).

Interannual variability

The skill of the ECMWF seasonal forecasting System 3 to predict the frequency of tropical storms is assessed by tracking the model tropical storms in the 11-member re-forecasts and comparing their frequency to observations from operational centres over the period 1990 to 2006. The period 1990–2006 was chosen because it is long enough to assess the skill of the model to predict the interannual variability of tropical storms, and short enough to reduce the impact of decadal variability.

The skill of System 3 to predict the interannual variability of tropical storms depends strongly on the starting date and the basin. Over the North Atlantic, the model has some moderate skill in predicting the number of tropical storms a few months in advance, with a linear correlation with observations of the order of 0.5 for the forecasts starting from April to August. Figure 6(a) shows the interannual variability of tropical storms for the forecasts starting on 1 July. The linear correlation is 0.56 and the RMS error is 3.6, which is lower than the RMS error of 4.3 obtained with climatology.

The model displays the strongest skill in predicting the interannual variability of tropical storm frequency over the Western North Pacific for the forecasts starting from January to April (see example in Figure 6(b) for the forecasts starting on 1 March) and the South Pacific for the forecasts starting from July to September (see example in Figure 6(c) for the forecasts starting on 1 September). Over those basins the linear correlation with observations exceeds 0.7. Over the other ocean basins the model has generally no skill in predicting the interannual variability of tropical storms, except maybe over the Australian basin for the forecasts starting in November and December.

	ATL	ENP	WNP	SIN	AUS	SPC
System 2	2.6	4.4	2.5	2.1	1.4	2.9
System 3	1.6	1.5	1.6	1.03	0.99	1.0

Table 1 Calibration factors applied to the number of tropical storms predicted by the seasonal forecasting systems over the north Atlantic Basin (ATL), Eastern North Pacific (ENP), Western North Pacific (WNP), South Indian Ocean (SIN), Australian Basin (AUS) and the South Pacific (SPC). The calibration factor depends on the forecast starting dates. Displayed are the calibration factors for the forecasts starting on 1 June for the basins in the northern hemisphere and 1 October for the basins in the southern hemisphere.

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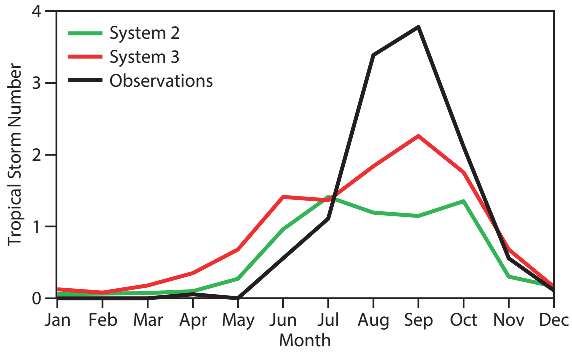

Figure 5 Seasonal cycle of tropical storm frequency over the North Atlantic in System 2, System 3 and observations for 1987–2004.

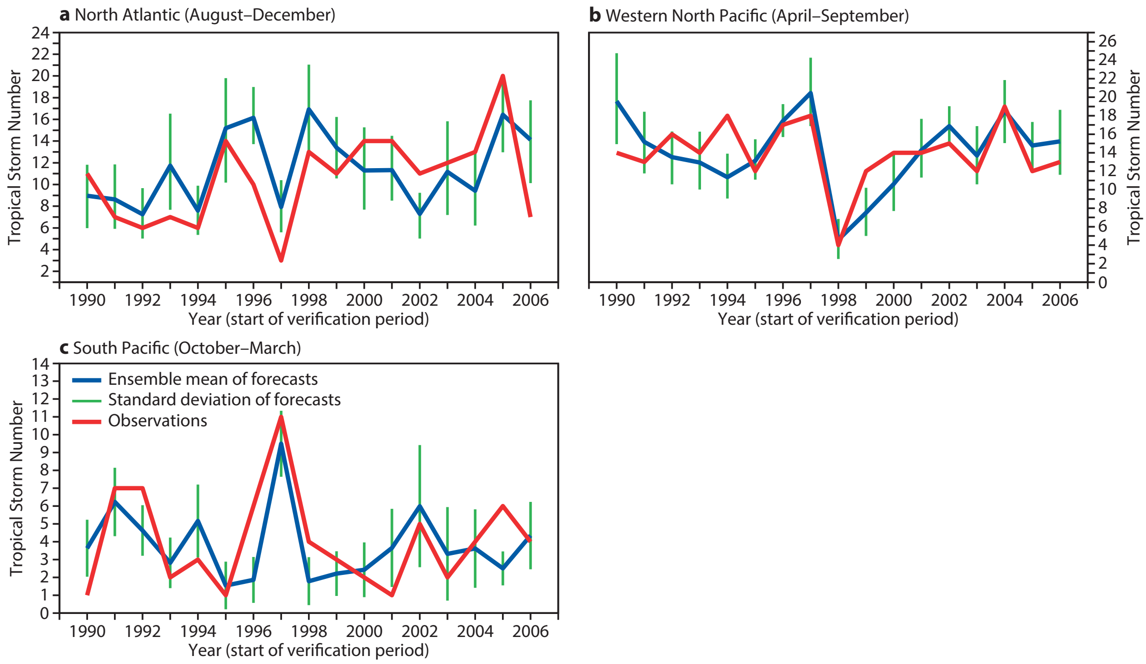

Figure 6 (a) Ensemble mean of the number of tropical storms over the North Atlantic for the period August to December from forecasts starting on 1 July for 1990 to 2005 using System 3. The solid blue line represents the ensemble mean of the forecast starting on 1 July and the vertical green line represents two standard deviations. The dotted red line corresponds to the observed number of tropical storms. (b) As (a) but for the Western North Pacific with the forecasts starting on 1 March and covering the period April to September. (c) As (a) but for the South Pacific with the forecasts starting on 1 September and covering the period October to March.

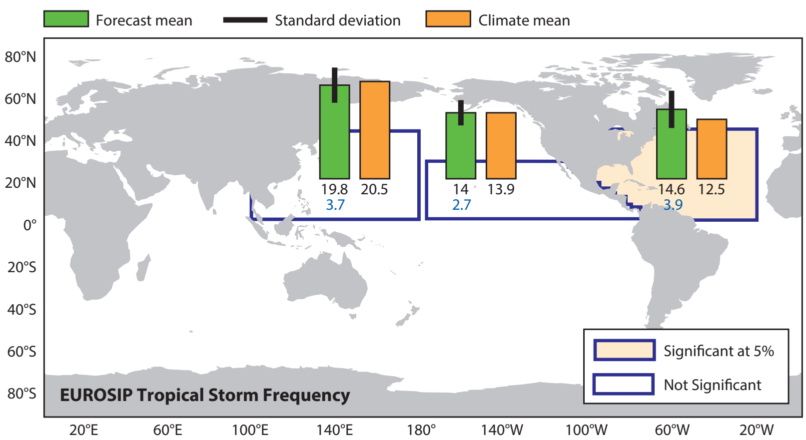

Figure 7 Same as Figure 1 but from EUROSIP and for the period June to October instead of June to November (EUROSIP forecasts are six-month long, whereas ECMWF System 3 forecasts are seven-months long).

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Multi-model operational forecasting

EUROSIP combines real-time seasonal forecasts from ECMWF System 3, the Met Office System 3 and Météo-France System 2. A detailed description of EUROSIP can be found at: www.ecmwf.int/products/forecasts/seasonal/forecast/forecast_charts/eurosip_doc.htm.

EUROSIP seasonal forecasts of tropical storms are produced by combining the forecasts of the individual models. The combination is performed by giving the same weight to all the models. Figure 7 shows an example of a EUROSIP forecast.

The skill of EUROSIP in predicting seasonal forecast of tropical storms has been assessed. Results suggest that the skill of EUROSIP is generally larger than that of the individual models. Over the North Atlantic for instance EUROSIP has stronger skill in predicting the interannual variability of tropical storms than ECMWF System 3 alone (see Table 2). The linear correlation between EUROSIP and observations exceeds 0.6 for the Atlantic forecasts starting from April to June.

Start of forecasts	Linear Correlation	
	ECMWF	EUROSIP
1 April forecast	0.49	0.68
1 May forecast	0.50	0.71
1 June forecast	0.51	0.74

Table 2 Linear correlation between the predicted number of tropical storms and the observed frequency during the period 1993–2006 (one of the EUROSIP models has no re-forecasts before 1993).

What's next?

Seasonal forecasts of tropical storm activity (frequency and mean genesis location) have been issued on a regular basis using the ECMWF seasonal forecasting system since 2001. Since March 2007, those forecasts are produced using System 3 instead of System 2. The increased resolution in System 3 helped to produce a more realistic climatology of tropical storms.

The present system has some skill in predicting the interannual variability of tropical storms over basins such as the Atlantic, Western North Pacific, Australian basin and the South Pacific. This is mostly a consequence of the skill of the ECMWF seasonal forecasting system to predict ENSO and tropical SST variability in general.

Future plans include investigating the skill of the model to predict the risk of landfall over specific regions. The clear improvement in tropical storm tracks from System 2 to System 3 might make it possible to produce direct forecasts of tropical storm landfall. Alternatively, statistical techniques could be applied to infer landfall probabilities from model outputs. The skill of the model to predict heavy precipitations associated to the tropical storms will also be investigated. This could be important for predicting the risk of floods or landslides.

The skill of the seasonal forecasting system to predict the frequency of hurricanes or typhoons (tropical storms with a maximum wind speed exceeding 32 m s–1) and some hurricane activity indices like ACE (Accumulated Cyclone Energy) is also being explored. Such statistics may be more useful than the current tropical storm predictions, since most of the damage is caused by hurricanes rather than by weak tropical storms. Thanks to its relative high resolution, System 3 produces a reasonable number of hurricanes, although none of them reach category 5. This makes it possible to issue hurricane forecasts using System 3.

Preliminary results suggest that System 3 has some skill in predicting the interannual variability of hurricanes or typhoons, particularly over the North Atlantic and Western North Pacific. For instance, the linear correlation between the observed number of hurricanes and the ensemble mean of the 1 July forecasts over the North Atlantic from 1990 to 2006 is 0.71.

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Further Reading

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