TECHNICAL MEMORANDUM

387

Seasonal forecasting of tropical cyclone landfall over Mozambique

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October 2002

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

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Abstract

The 2000 tropical cyclone season over the South Indian Ocean (SIO) was exceptional in terms of tropical cyclone landfall over Mozambique. Observed data suggest that SIO tropical cyclones have a track significantly more zonal during a La-Niña event and tend to be more frequent when local SSTs are warmer. The combination of both conditions happened during the 2000 SIO tropical cyclone season and may explain the exceptional number of tropical cyclone landfalls over Mozambique during that season. A set of experiments using an atmospheric general circulation model (AGCM) forced by prescribed SSTs confirms the role of La-Niña conditions and warmer local SSTs on the frequency of tropical cyclone landfalls over Mozambique. This also suggests that a numerical model can simulate the mechanisms responsible for the exceptional 2000 tropical cyclone season, and therefore could be used to explicitly predict the risk of landfall over Mozambique.

The European Centre for Medium-Range Weather Forecasting (ECMWF) operational seasonal forecasting system does not have a sufficiently high horizontal resolution to produce meaningful statistics on tropical cyclone landfalls. However, with a higher horizontal resolution (about 100 km), this system simulates a realistic number of tropical cyclone landfalls over Mozambique. This ”high-resolution” coupled model has been integrated for 3 months starting on 1st January each of year from 1987 to 2000. The hindcast produces significantly more tropical cyclone landfalls in 2000 than in any other year, and years with a predicted high risk of landfall generally coincide with years of observed tropical cyclone landfall.

1 Introduction

The 2000 tropical cyclone season over the South Indian Ocean was exceptional in term of tropical cyclone landfall over Mozambique, with serious consequences. In February 2000, Mozambique was already devastated by severe floodings after two weeks of steady rain before the landfall of tropical cyclone Eline with hurricane intensity (maximum sustained wind larger than 32 m/s) on 25 February 2000. Eline brought more than 20 cm of precipitation per day over the already flooded region, creating a catastrophic situation. An estimated 700 people died and 2 million people were affected by the flood. At the beginning of April, a second tropical cyclone with hurricane intensity (Hudah) made a landfall over the northern part of Mozambique, but fortunately without the devastating consequences of tropical cyclone Eline.

Although tropical cyclones cannot be blamed for all the flooding over Mozambique, they played a dramatic role in worsening an already serious situation. Such strong tropical cyclone activity over Mozambique (2 landfalls) is rare. According to historical records (Neumann et al 1993), Mozambique had been hit by more than one tropical cyclone only twice in the previous 60 years (1962 and 1988), and never by more than one tropical cyclone with hurricane intensity. In most years, Mozambique does not suffer any tropical cyclone landfall, since tropical cyclones tend to have a southward recurvature well before reaching the Africa coast, thus sparing Mozambique. Therefore, the 2000 tropical cyclone season over the SIO can be viewed as exceptional and the seasonal forecast of tropical cyclone landfall over Mozambique could be a valuable tool for water resource management.

It would be excessively optimistic to think that the occurrence of one specific landfall could be predicted months in advance, since the mesoscale conditions associated with that particular landfall have a predictability of the order of a few days at most. However, large-scale conditions, which might be predicted months in advance, can impact the frequency and tracks of tropical cyclones, and as a consequence the risk of landfall. The present paper will evaluate the predictability of the risk of landfall over Mozambique, using both observations and numerical model integrations. In Section 2, a 51-year record of observed tropical cyclone tracks from Neumann et al (1993) and reanalyses data from NCEP (Kalnay et al 1996) will be used in order to identify predictors and potential physical mechanisms responsible for the year-to-year change in the risk of landfall over Mozambique. Observations are not sufficient to prove all the relations, but lead into model studies in the the third section, which will describe sensitivity experiments using an atmospheric GCM (AGCM) forced by prescribed SSTs. The goal of these experiments is to isolate the impact of the different predictors on the simulated tropical cyclones. This will demonstrate the validity of the physical mechanisms identified in the observational study and that they can be reproduced in a numerical model. Section 4 will evaluate the skill of coupled GCMs to explicitly predict the risk of landfall over Mozambique. The last section will present a discussion of the main results of this paper.

2 Observations

In the present paper, tropical cyclones are defined as tropical cyclonic systems with a maximum sustained wind larger than 17 m/s. The tropical cyclone genesis location refers to the position where the tropical cyclone maximum wind velocity exceeds 17 m/s for the first time. Intense tropical cyclones are defined as tropical cyclones with hurricane intensity (32 m/s). The SIO is defined as the region west of 150E as in Gray (1979). SIO tropical cyclones are defined as the tropical cyclones with at least a portion of their track within SIO, though the genesis location does not necessarily need to be within SIO. Most SIO tropical cyclones occur during a specific period of the year: from September to April; the tropical cyclone season 2000 for example refers to the period September 1999 to April 2000. All the statistics concerning observed tropical cyclones have been obtained from the Joint Typhoon Warning Center (JTWC, Guam), and Neuman et al (1993). The tropical cyclone record over the SIO prior to the use of meteorological satellites in the 1960s may be less reliable, since they were based mostly on ship reports. On the other hand, these statistics do not display any obvious difference between the periods prior to and after the introduction of satellite data as is the case over the eastern North Pacific: the statistics concerning tropical cyclone landfall over Mozambique since 1950 may be reliable, because of the large population living in the area.

A comparison between the tropical cyclone tracks in 2000, 1999 and 1998 (Fig. 1) suggests a significant interannual variability in the frequency and tropical cyclone tracks. In 2000, the tropical cyclone tracks were generally more zonal than in 1998, where all the tracks west of 80E, have a strong southward component. In 2000, the tropical cyclones Eline and Hudah, had a genesis in the eastern edge of the basin with a landfall over Mozambique after weeks of a very unusual zonal track. In 1999, tropical cyclones tracks were also very zonal, but the tropical cyclone activity west of 60E was low, with most tropical cyclones dying between 50E and 90E. In addition, the number of intense tropical cyclones was significantly lower than climatology in 1999 and significantly higher in 2000. In 1998, the tropical storm tracks were more poleward than in 2000, and most tropical storms with a genesis location in the eastern part of the basin recurved east of Madagascar. None of these storms crossed Madagascar. This interannual variability in tropical storm statistics is likely to induce an interannual variability in the risk of landfall over Mozambique. In this section, we will discuss what factors can explain the interannual variability in tropical cyclone frequency and tracks in the SIO, and how this impacts the risk of landfall over Mozambique using observed data.

The interannual variability of tropical cyclone statistics can often be related to the interannual variability of the large-scale circulation. The *frequency* of tropical cyclones is sensitive to the vertical shear of the horizontal wind defined as the amplitude of the difference between the wind in the upper and the lower troposphere (see for instance Gray 1979, Frank 1987, Vitart and Anderson 2001) and SST anomalies (Saunders and Harris 1997, Goldenberg et al 1996, Vitart and Anderson 2001). Low vertical wind shear and warm SST anomalies are conducive to more tropical cyclone activity. Variability in tropical cyclone *tracks* has also been related to the large-scale circulation. To a first order, tropical cyclone motion is attributed to the environmental wind circulation. Dong and Neumann (1986) indicate the optimum level of 400 mb for hurricanes and 700 mb for tropical cyclones for the Atlantic basin. However, vertical means over various depths of the atmosphere are usually considered for modelling the tracks of tropical cyclones rather than using a single level (Holland 1983).

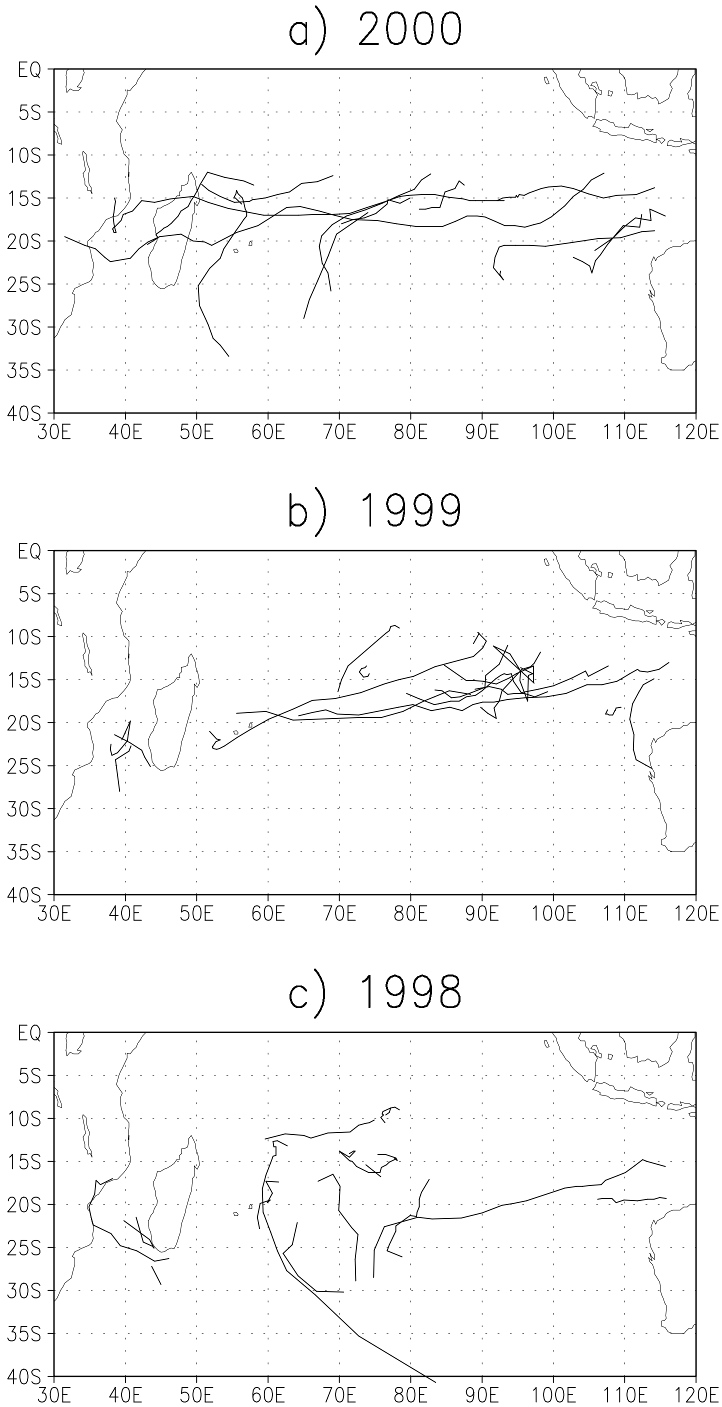

Figure 1: Tropical storm tracks observed during a) the 2000 tropical cyclone season, b) the 1999 tropical cyclone season, and c) the 1998 tropical cyclone season. This figure suggests a strong seasonal variability in the tracks of tropical cyclones over the South Indian Ocean

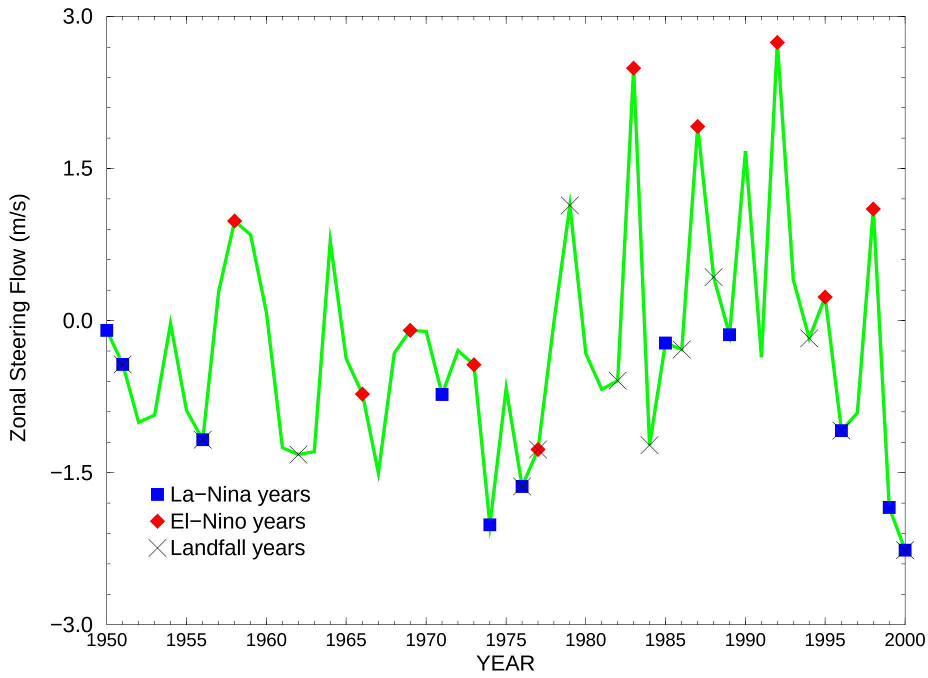

Figure 2: Interannual variability of the zonal steering flow over the SIO (50E-100E, 8S-22S) and averaged from 1st January to 31st March. The mean is close to 0 m/s. Crosses indicate years with landfall, squares years with La-Niña conditions, and diamonds years with El-Niño conditions. El-Niño and La-Niña seasons are defined as the seasons when the NINO3.4 SSTs averaged over the period January to March are one standard deviation above and below the 1950-2000 climatology.

2.1 Impact of the zonal steering flow

The zonal wind from the National Center for Environmental Prediction (NCEP) reanalysis (Kalnay et al., 1996) has been vertically averaged from 200mb to 850mb over the SIO tropical cyclone main development region (40E-100E, 10S-25S) and has been averaged over the period from 1st January to 31st March (the peak period of the SIO tropical cyclone season). It will henceforth be referred to as the SIO zonal steering flow. Figure 2 displays the interannual variability of the SIO zonal steering flow from 1950 to 2000. Considering one single level instead of averaging over a vertical column would produce similar results. The SIO zonal steering flow displays a large interannual variability. It is not clear if the discontinuity around 1980 is due to a change in the quality of the atmospheric data or due to an interdecadal variability of the atmospheric circulation.

In order to evaluate if the interannual variability of the zonal steering flow is strong enough to generate an interannual variability of tropical cyclone motion, a composite of the tropical cyclone tracks during each season when the zonal steering flow is one standard deviation below average and one standard deviation above average has been created (not shown). For each composite of tropical cyclone tracks, the direction of motion has been defined as the difference of longitude between day 5 and day 1 divided by the difference of latitude between day 5 and day 1. The Kolmogorov-Smirnov test (KS test) (Knuth 1979) indicates that the mean direction of motion of the tropical cyclones for the low zonal steering flow case is significantly more zonal than the mean direction of motion for the high zonal steering flow case with a confidence level higher than 97%. As a consequence, the spatial distribution of tropical cyclone days calculated from tropical storms with a genesis location between 50E and 120E displays significant differences between the two composites (Fig. 3). When the zonal steering flow is one standard deviation below average, the tropical cyclone activity extends along a band between 20S and 10S east of Madagascar, and between 25S and 15S west of Madagascar (Fig. 3a), with about the same magnitude on both sides of the island. When the zonal steering flow is one standard deviation above average, the tropical cyclones tend to recurve just east of Madagascar (Fig 3b), with more tropical cyclone activity between 50E and 60E (Fig. 3c). At this location, the amplitude of the difference represents 70% of the climatology, suggesting that the zonal steering flow has a significant impact on the tropical cyclone activity off the coast of Mozambique. Increased tropical cyclone activity to the west of Madagascar is likely to increase the risk of landfall over Mozambique.

The years with tropical cyclone landfall are marked with a cross on Figure 2. According to the KS-test, years with landfall display a zonal steering flow significantly more negative (95% significance) than years without landfall. During the past 50 years, tropical cyclones have hit Mozambique during 25% of the total number of years. When the zonal steering flow is one standard deviation below average, the percentage increases to 58%, but is reduced to 11% when the zonal steering flow is one standard deviation above average. This suggests that the risk of landfall over Mozambique is indeed related to the zonal steering flow, with a probability about 5 times higher when the zonal steering flow is one standard deviation below average than when it is one standard deviation above average. If the zonal steering flow could be predicted a month or more in advance, it could be used as a predictor for the risk of landfall over Mozambique.

2.2 Impact of SIO SSTs

Several observational (Saunders and Harris 1997; Goldenberg and Shapiro 1996) and model studies (Vitart and Anderson 2001) have demonstrated that warmer SSTs are conducive to a significant increase of tropical cyclone activity over the Atlantic. SSTs have also an effect on the frequency of tropical cyclones over the SIO. Jury (1999) uses SSTs averaged over the region 8S-22S and 50E-70E as a predictor for the frequency of tropical cyclones over the South Indian Ocean. Xie et al (2002) demonstrate that warmer SSTs produced by the propagation of Rossby waves across the South Indian Ocean lead to significantly more tropical cyclone days.

All the SIO tropical cyclone seasons have been classified according to the zonal steering flow and anomalous SST averaged over the region where most tropical cyclones originate (50E-110E; 8S-22S) and over the period January to March (Fig. 4a). The years with landfall are marked with a square. According to Figure 4a, there is a strong correlation between SSTs and zonal steering flow. Years with more positive zonal steering flow coincide with years with high SIO SSTs. As discussed in the previous subsection, the percentage of years with landfall increases with more negative zonal steering flow. Overall, years with higher SSTs do not display more frequent landfalls. However, when the zonal steering flow is more negative, the percentage of years with landfall increases with warmer SSTs. If we consider only the years when the zonal steering flow is one standard deviation below average, then years with landfall display significantly warmer SSTs, a result that is significant at the 90% level according to the KS-test. Figure 4 has been divided into four regions. Region I is the region with low zonal steering flow is one standard deviation below average (less than about -0.9 m/s) and positive SST anomalies (calculated from the 1949-2000 climatology). During the past 52 years, only 4 seasons are within this domain. Three of them had a landfall over Mozambique (75% of the cases). Over region II (steering flow one standard deviation below average and negative SST anomalies), the percentage of years with landfall decreases to 36%, which is about half that in region I. Over regions III and IV, where the zonal steering flow is more positive than in regions I and II, SST anomalies do not have a significant impact since the percentage of seasons with landfalls is about the same in both areas. This result suggests that SSTs have an impact on the risk of landfall only when the zonal steering flow is sufficiently negative. This can be explained by the fact that if the zonal steering flow is more positive, the tropical cyclone tracks are more poleward, and therefore landfalls over

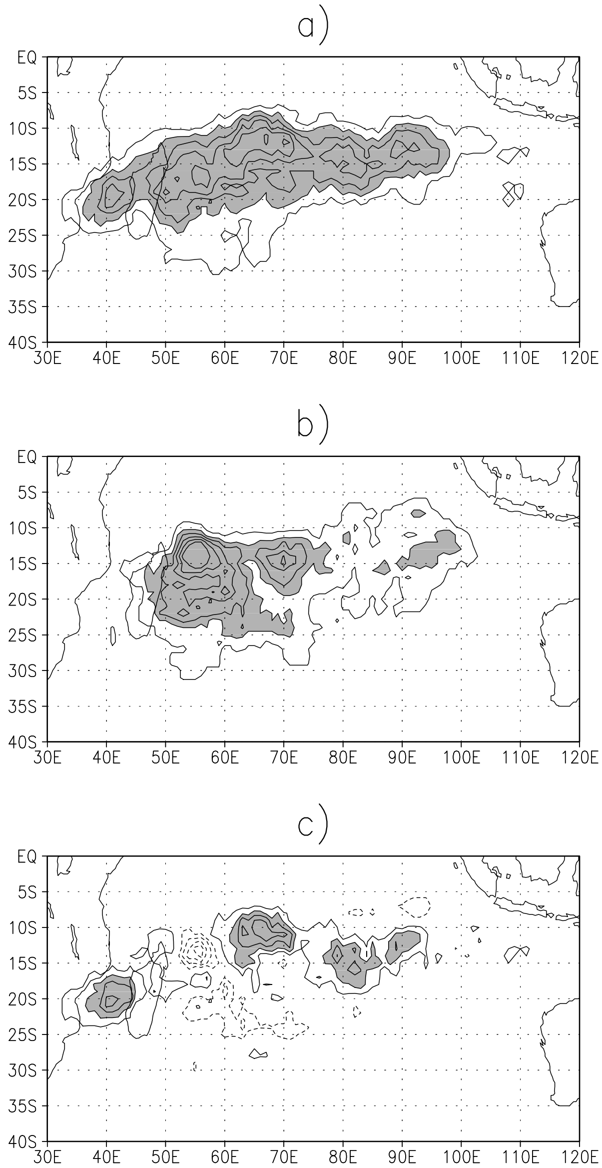

Figure 3: Observed tropical cyclone days per season on a $4^o x 4^o$ latitude grid when the zonal steering flow is a) one standard deviation below climatology (defined over the period 1950-2000), and b) one standard deviation above climatology. The difference between a) and b) is displayed in Figure c). The contour interval is 0.5 tropical cyclone day and the first contour is 0.5 tropical cyclone day. Shaded areas represent regions with more than 1 tropical cyclone day. Only tropical storms with a genesis location between 50E and 120E have been considered.

Mozambique are unlikely whatever the number of cyclones. On the other hand, more negative zonal steering flow is conducive to zonal tropical cyclone tracks and so more frequent or more intense cyclones will increase the risk of landfalls over Mozambique. Therefore the difference of tropical cyclone landfall statistics between the two La-Niña seasons 1999 and 2000 could be explained by the fact that 2000 is in region I, whereas the inactive tropical cyclone season 1999 is in Region II.

In summary, the zonal steering flow can be considered as a first order predictor of the risk of landfall over Mozambique. SSTs seem to have an impact on the risk of landfall only when the zonal steering flow is sufficiently negative. Although figure 4a strongly suggests that local SSTs have an impact on the risk of landfalls over Mozambique, the data record is not long enough (only 4 years are in region I) to prove the significance of this last result, but in section 3, it will be shown that this result is consistent with model simulations.

2.3 Impact of the vertical wind shear

The vertical wind shear is known to have a significant impact on Atlantic tropical cyclones (Gray 1983, Goldenberg and Shapiro 1996, Vitart and Anderson 2001) and explains mostly why the Atlantic tropical storm activity is significantly reduced during El-Niño events. The impact of the vertical wind shear on the tropical cyclone frequency is due to the ventilation of the warm core above the center of the cyclone. A figure similar to figure 4 has been produced (not shown), but this time the tropical cyclone seasons have been classified according to vertical wind shear and steering wind. Unlike with SSTs, if we consider only the years with zonal steering flow one standard deviation below average, there is no significant difference of vertical wind shear between the years with tropical cyclone landfalls and those without. Therefore, only the steering wind and the SIO SSTs will be considered as predictors for the risk of landfall over Mozambique in the rest of this paper.

2.4 Role of ENSO

ENSO is the most important source of interannual variability in the Tropics. It is often used as a predictor for tropical cyclone activity over the Atlantic (Gray et al 1992), the western North Pacific (Chan et al 1998) and the Australian Basin (Nicholls 1992). The present subsection will investigate its impact on the zonal steering flow and SIO SSTs. In the present paper, El-Niño seasons are defined as the seasons when the NINO3.4 SSTs (120W-170W, 5N-5S) averaged over the period January to March are one standard deviation above the 1950-2000 climatology, and La-Niña seasons when NINO3.4 SSTs are one standard deviation below climatology. This definition of ENSO years may not be consistent with other definitions in which an ENSO year is defined as the year where the ENSO event starts, as in Bove et al (1998) for instance. Following our definition, there have been 10 El-Niño seasons and 11 La-Niña seasons over the period 1950 to 2000. In figure 2, El-Niño years are marked with diamonds and La-Niña years with squares. It appears clearly that El-Niño seasons generally correspond to positive anomalies of the zonal steering flow, whereas La-Niña seasons generally correspond to negative anomalies. This is confirmed by a KS-test which indicates that the 10 El-Niño years display a zonal steering flow significantly more positive than La-Niña years with a significance larger than 95%. The impact of ENSO on the zonal steering flow over the SIO suffers some exceptions, such as 1989, which was a La-Niña season but with a positive zonal steering flow over the SIO, or 1990 which was not an El-Niño season, but which displayed a very high and positive zonal steering flow. Therefore there is no perfect match between ENSO and the zonal steering flow over the SIO, but El-Niño significantly increases the probability of a positive zonal steering flow, whereas La-Niña increases the risk of a negative zonal steering flow. The next Section will demonstrate that the strong link between ENSO and the zonal steering flow is due to a remote impact of Pacific equatorial SSTs on the wind circulation over the SIO. Because of its significant link with the zonal steering flow, ENSO is likely to impact the risk of landfall over Mozambique. Historical records of tropical cyclones a)

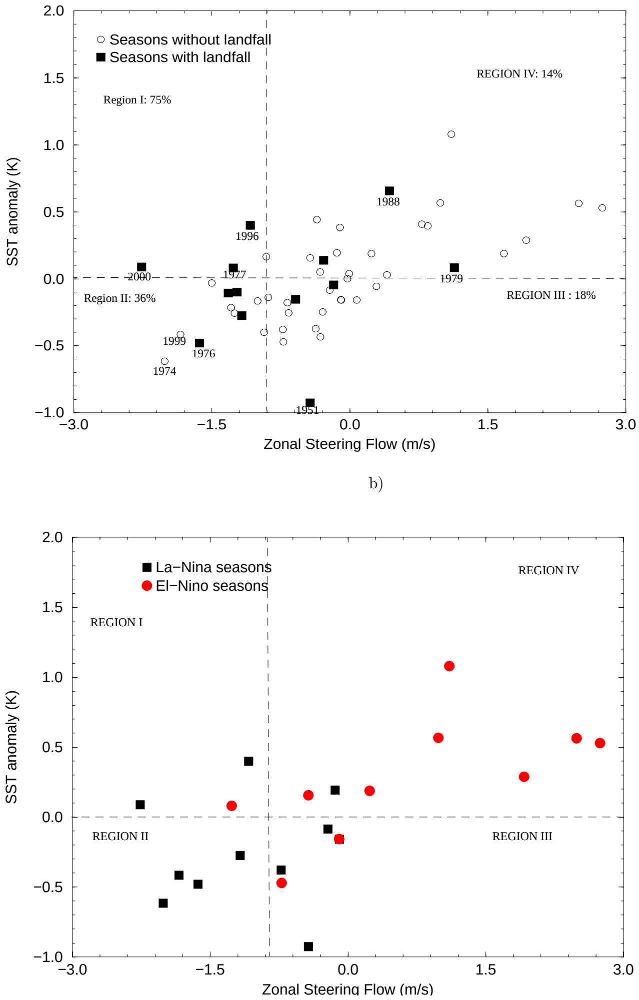

Figure 4: a) Distribution of all the tropical cyclone seasons from 1950 to 2000 as a function of the zonal steering flow over the SIO (x-axis) and SIO SST anomaly (y-axis). Squares represent years with a landfall over Mozambique and circles represent years without a landfall. Four regions are defined. In region I, the SST anomaly is greater than 0 and the zonal steering flow is one standard deviation below climatology. This region displays the largest percentage of seasons with landfalls, and 2000 is within this region. Region II corresponds to zonal steering flow below one standard deviation and negative SST anomalies. The 1999 tropical cyclone season is in this region. Regions III and IV correspond to a zonal steering flow above about -0.9 m/s. These regions display the lowest frequency of tropical cyclone landfall. b) Distribution of all the El-Niño (circles) and La-Niña seasons (squares) from 1950 to 2000 as a function of SIO SST anomaly (y-axis) and zonal steering flow over the SIO (x-axis).

over the SIO show that tropical cyclone landfalls occurred during 25% of all the tropical cyclone seasons. This percentage increases to 45% during La-Niña seasons and reduces to 10% during El-Niño seasons. Therefore, the probability of landfall over Mozambique seems to be 4.5 times higher during a La-Niña year than during an El-Niño year. Although the data is too short to prove its significance, this result suggests that ENSO impacts the risk of landfall over Mozambique. Because of its link with the zonal steering flow, ENSO could replace the zonal steering flow as a predictor for the risk of landfall over Mozambique.

ENSO also impacts local SST over the SIO. Xie et al (2002) discuss the interannual variability of SIO SSTs, and found that ENSO is the dominant forcing for SIO thermocline variability. When an El-Niño event takes place, anomalous easterlies appear in the equatorial Indian Ocean, forcing a westward-propagating down-welling Rossby wave in the SIO. This explains why the SSTs during the 10 El-Niño seasons are significantly warmer than during the 11 La-Niña seasons, with a significance exceeding 95% according to the KS-test. The impact of ENSO on both the zonal steering flow and SIO SSTs explains the significant correlation (0.6) between these two quantities.

El-Niño and La-Niña seasons since 1950 have been classified according to SST anomalies and the zonal steering flow in a similar way to figure 4a (Fig 4b). It appears clearly that El-Niño years largely outnumber La-Niña years in region IV, whereas La-Niña seasons greatly outnumber El-Niño seasons in regions I and II, where the probability of landfall is higher. However, if we consider only REGION I and II, La Niña seasons do not display significantly lower SSTs than the non La-Niña seasons of the same region. Xie et al (2002) identified SST variability off Sumatra, which is not necessarily linked to ENSO, having an impact on the SST variability over the SIO. Therefore, some of the SIO SST variability is not related to ENSO. This variability may explain why La-Niña years like 1996 and 2000 displayed warmer SSTs than expected for a La-Niña season, and therefore why tropical storm landfalls occurred during these seasons.

In summary, La-Niña conditions over the tropical Pacific and positive SST anomalies in the SIO seem to be conducive to an increase of tropical cyclone landfall over Mozambique. However, the data length (51 years) is too short to prove this result, since only two years (both with landfalls) fulfill both conditions. However, the use of GCM integrations supports this result as will be discussed in the next section.

3 Sensitivity Studies using a high resolution AGCM

A series of sensitivity studies using an AGCM forced by prescribed SSTs has been performed in order to evaluate the impact of ENSO and SIO SSTs on the tropical cyclones simulated by the AGCM. An objective procedure for tracking model tropical cyclones has been described in Vitart and Stockdale (2001). This procedure has been improved in order to produce more realistic tracks of tropical cyclones. The criteria for detecting tropical cyclones have been relaxed, so that all the criteria need to be verified only twice along the whole trajectory, instead of at all times as in Vitart and Stockdale (2001). In addition, the maximum permitted distance between two successive tropical cyclone positions has been increased. These changes improve the realism of the tropical cyclone tracks and help to capture portions of the tracks where the tropical cyclone has the intensity of a tropical depression. This reduces the risk of counting twice the same tropical cyclone if its intensity decreases below the threshold defining a tropical cyclone and then reintensifies. The tropical cyclone tracks with this new algorithm are longer than those obtained with the original tropical cyclone tracking procedure, which is important for the study of tropical cyclone landfall. In order to evaluate its skill in detecting tropical cyclones, the objective procedure has been applied to 9 months of ECMWF operational analyses from 1st September 1999 to 1st June 2000 (the 2000 tropical cyclone season). The operational analyses have been interpolated to the same horizontal resolution as in the numerical model used for the present sensitivity study (TL159, which represents a resolution of approximately 1.125^ox1.125^o. Figure 5 displays the tropical cyclone tracks detected

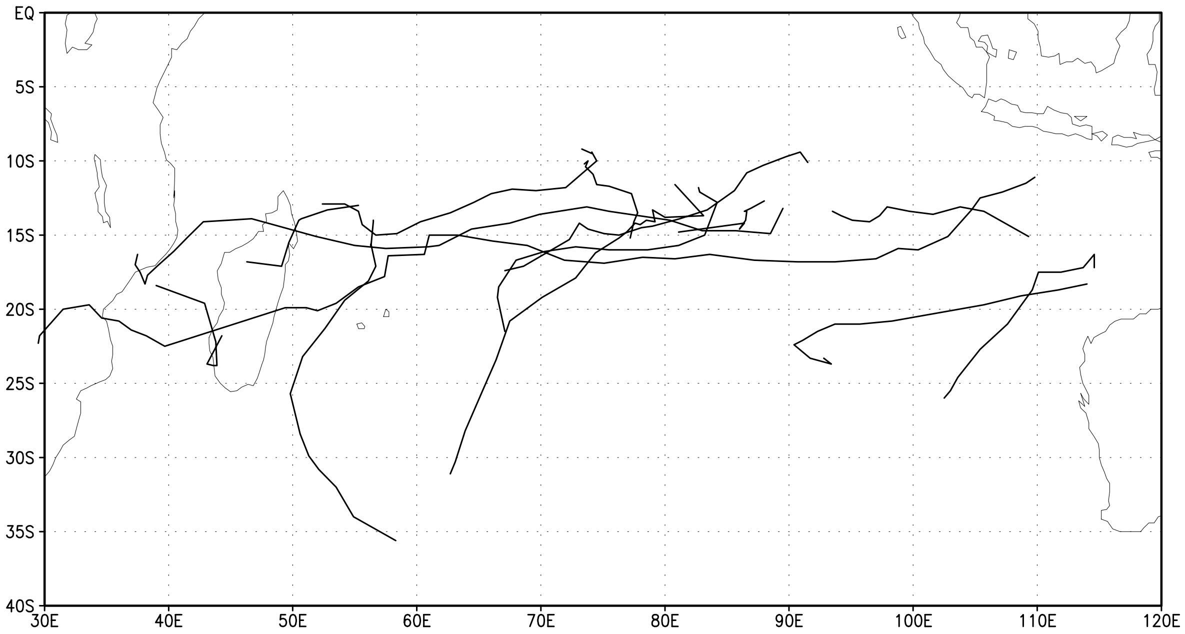

Figure 5: Tropical cyclone tracks over the SIO detected when applying the objective procedure for tracking tropical cyclones to the ECMWF operation analysis interpolated to a $1.125^o x 1.125^o$ *horizontal grid from September 1999 to June 2000.*

by the new objective procedure, and can be compared to the top panel of Figure 1, which displays the tropical cyclone tracks from JTWC during the same period. Ten tropical cyclones have been observed over the SIO during the 2000 tropical cyclone season by JTWC. The tropical cyclone tracking procedure detects 9 of them. Tropical cyclone Kirrily was not detected because it is too weak in the ECMWF operational analysis. On the other hand, the procedure detects 2 additional systems that are not observed by JTWC. They were classified as tropical depressions by JTWC, but in the ECMWF operational analysis, they have tropical storm intensity, and one of them even has the intensity of a hurricane. In summary, the objective procedure seems to detect tropical cyclones in the analysis rather well. The two false alarms and the non-detection of tropical cyclone Kirrily are more likely due to inconsistencies between ECMWF operational analyses and what other operational centers have classified as tropical storms, than due to deficiencies in the tropical cyclone detection algorithm. The tracks of the detected tropical cyclones look realistic, and consistent with observed tracks. Most importantly for the present paper, the two landfalls of Leon-Eline and Hudah are well detected by the objective procedure (Figure 5), and no non-observed landfall was detected.

In the present Section, the AGCM is IFS cycle 23r4. The horizontal resolution is TL159 corresponding to a grid resolution of about 1.125^o latitude with 40 vertical levels. The AGCM has been integrated for 3 months forced by prescribed SSTs in order to determine if the AGCM can simulate interannual variability in the frequency of landfall over Mozambique. These experiments will respectively be referred to as EXP1998, EXP1999 and EXP2000. Since the length of the model integrations exceeds the limits of deterministic predictability, a single model integration is certainly not enough to evaluate the risk of landfall over Mozambique. Therefore, the AGCM has been integrated with 20 different initial conditions, taken from the ECMWF operational analysis from 15 November 1999 to 21 December 1999, at 2-day intervals. In order to remove the effect of the initial state, the first 2 weeks of the forecasts have been discarded. Since the starting dates are not the same, the period covered by the integration varies from one member of the ensemble to another, but this is unlikely to generate significant differences in tropical cyclone numbers. In addition all the sets of ensemble runs have identical starting dates, therefore this will not have any impact on the comparison between the different experiments; the initial conditions vary from one member of the ensemble to another, but are the same in all the sets of experiments. The key aspect of the design of the 3 sets of experiments is that the only difference between the experiments is the SST forcing. Therefore all the significant differences in tropical storm statistics and large-scale circulation between the 20-member ensemble integrations can only be attributed to the difference in SSTs.

3.1 Impact of ENSO

To evaluate the impact of ENSO on model tropical cyclones, a 20-member integration of the AGCM forced by SSTs of 1999/2000 (EXP2000) has been compared to a 20-member ensemble forced by SSTs of 1997/1998 (EXP1998). In EXP1998, the atmospheric model has been forced by observed SSTs during one of the strongest El-Niño events on record. In EXP2000, the prescribed SSTs correspond to strong La Niña conditions. The present subsection will explore the differences in the large-scale circulation and the tropical storm statistics in the two sets of experiments. However, SSTs outside the tropical Pacific region could also have an impact on the statistics of tropical cyclones. Therefore, in order to isolate the impact of tropical Pacific SSTs, two additional 20-member ensembles have been generated. In EXP2000_PAC, the prescribed SSTs correspond to the 1997/1998 season everywhere, except over the tropical Pacific (120E-200E, 20N-20S) where SSTs of 1999/2000 have been imposed. Therefore, the only difference between EXP1998 and EXP2000_Pac is the SST forcing over the tropical Pacific. EXP1998_Pac has the opposite setting to EXP2000_Pac: i.e. SSTs of 1999/2000 are used everywhere except over the tropical Pacific, where SSTs of 1997/1998 are imposed. A summary of the experiment design is displayed in Table 1.

Experiment name	SSTs over tropical Pacific	SSTs elsewhere
EXP1998	1997/1998	1997/1998
EXP2000	1999/2000	1999/2000
EXP1998_Pac	1997/1998	1999/2000
EXP2000_Pac	1999/2000	1997/1998

Table 1: Description of the experiments EXP2000, EXP1998, EXP2000_Pac and EXP1998_Pac

3.1.1 Impact on the zonal steering flow

Figure 6a displays the difference in the NCEP reanalysis between the zonal steering flow averaged over the period December-January-February 2000 and the zonal steering flow averaged over the period December-January-February 1998. Over the eastern tropical Pacific, the zonal steering flow is significantly lower in 1998 than in 2000. This is probably due to the fact, that over the tropical Pacific, El-Niño is conducive to an increase of deep convection, which increases the coherence between upper and lower tropospheric flows, and therefore reduces the zonal steering flow. Over the South Indian Ocean, the zonal steering flow is weaker in 2000 than in 1998 over the main tropical cyclone development region (between 10S and 20S). It is not clear at this point if this is a consequence of ENSO or it is due to other factors, such as local SSTs. The difference between the zonal steering flow simulated by EXP2000 and EXP1998 (Fig 6b) displays a pattern that is very similar to the one from the NCEP reanalysis, although its amplitude over the eastern Pacific seems to be underestimated by

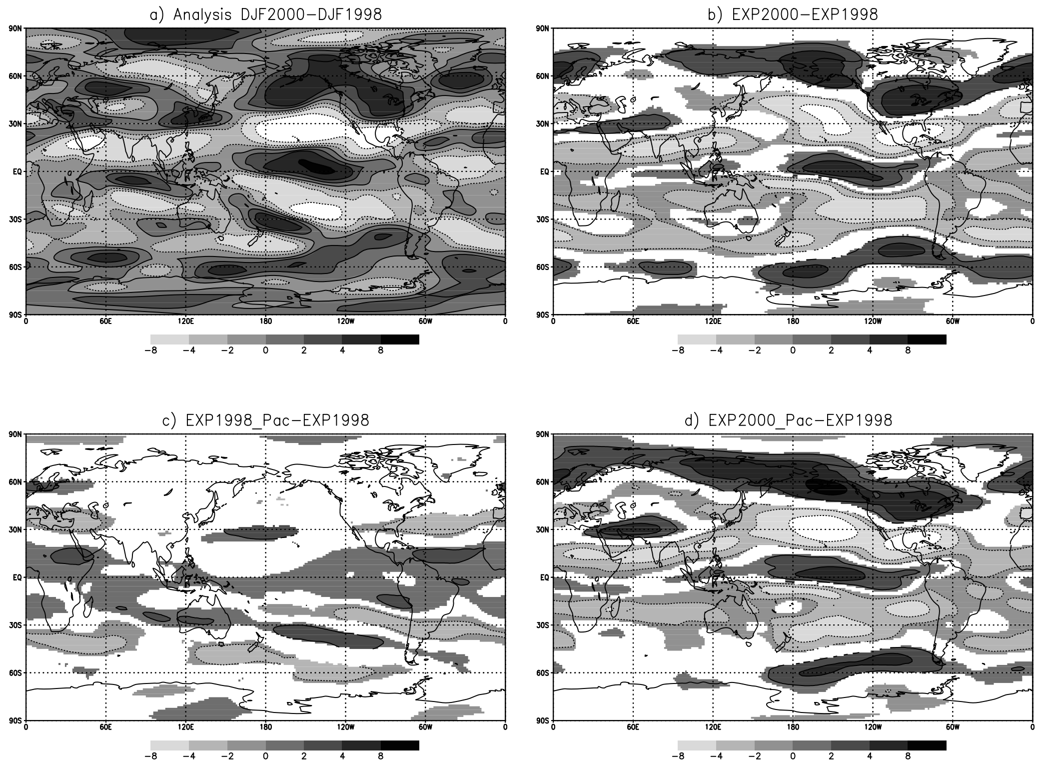

Figure 6: Difference of zonal steering flow between a) the zonal steering flow (m/s) averaged over the period from 1st December 1999 to 1st March 2000 and the zonal steering flow averaged from 1st December 1997 to 1st March 1998 in the NCEP reanalysis, b) EXP2000 and EXP1998, c) EXP1998_Pac and EXP1998 and d) EXP2000_Pac and EXP1998. Dotted lines represent negative values. This figure shows that both EXP2000 and EXP2000_Pac simulate similar patterns with a significant reduction of zonal steering flow over the main SIO tropical storm development region. On the other hand, the difference between EXP1998_Pac and EXP1998 is much smaller in amplitude than between EXP2000 and EXP1998, suggesting that tropical Pacific SSTs are responsible for most of these anomalous patterns. In b), c), d), regions where the WMW test detects a significance in the difference lower than 95% are blanked out.

the model. Over the South Indian Ocean, EXP2000 simulates a zonal steering flow significantly lower than in EXP1998, with a level of confidence larger than 99% according to the KS- test.

In order to estimate if the difference in zonal steering flow is due to a remote impact of eastern Pacific SSTs, the zonal steering flows in EXP2000_Pac and EXP1998_Pac have been compared to the zonal steering flow in EXP1998 (Figs 6c and 6d). The difference between the zonal steering flow of EXP2000_Pac and EXP1998 is similar to the difference between EXP2000 and EXP1998. In particular the zonal steering flow over the SIO is significantly lower in EXP2000_PAC than in EXP1998. Since the only difference between EXP2000_Pac and EXP1998 is the tropical Pacific SSTs, this suggests that the reduction of zonal steering flow simulated by the model between 1999/2000 and 1997/1998 is due to a teleconnection from the Pacific. EXP1998_Pac and EXP1998 have the same SSTs over the tropical Pacific, but different SSTs elsewhere. EXP1998_Pac does not display a significant decrease of zonal steering flow compared to EXP1998 (Fig 6c), indicating that SSTs outside the tropical Pacific have a small effect and supporting the result that the significant reduction of zonal steering flow between EXP2000 and EXP1998 is due to a remote impact of tropical Pacific SSTs, and therefore to ENSO.

3.1.2 Impact on the vertical wind shear

The model simulates a realistic variability of vertical wind shear between 1998 and 2000, although the model tends to underestimate the intensity of its interannual variability. In particular, the model simulates a vertical wind shear that is significantly weaker over the SIO tropical storm development region in 2000 than in 1998, as observed (not shown). Over this region, the difference in vertical wind shear in the model exceeds 4 m/s, which is probably enough to significantly impact the frequency of tropical cyclones. EXP2000_PAC simulates a vertical wind shear over the SIO that is significantly lower than in EXP1998. This suggests that the tropical Pacific SSTs have also a significant impact on the vertical wind shear over the SIO. EXP2000_PAC simulates a vertical wind shear that is significantly less than in EXP2000, suggesting that other SSTs, most likely local SSTs, have an impact on the vertical wind shear over the SIO. This is confirmed with EXP1998_PAC, which simulates a vertical wind shear over the SIO that is significantly higher than in EXP1998. The amplitude of this difference is close to the amplitude of the remote impact of the tropical Pacific SSTs on the vertical wind shear over the SIO.

3.2 Impact on tropical storm statistics

a) Tropical storm frequency

The tropical cyclones simulated by the AGCM have been tracked using the algorithm described in the previous section. Table 2 displays the frequency of tropical cyclones simulated in EXP1998, EXP2000, EXP1998_Pac and EXP2000_Pac. Table 3 displays the observed frequency. By comparing Table 2 with Table 3, it appears that the model simulates less than half as many tropical cyclones as observed. The low frequency of model tropical storms in the ECMWF seasonal forecasting system has been discussed in Vitart and Stockdale (2001). According to this paper, the frequency of model tropical cyclones is more sensitive to the cumulus parameterization of the AGCM than to its horizontal resolution and the cumulus-parameterization scheme used in the ECMWF atmospheric model produces an atmosphere that is too stable, making it more difficult for tropical cyclones to form.

Experiment	Frequency	Landfall	Landfall ratio
EXP2000	3.7	0.7	0.19
EXP1998	2.1	0.05	0.02
EXP2000_Pac	6.7	1.3	0.20
EXP1998_Pac	1.2	0.0	0.00

Table 2: Tropical cyclone frequency, number of landfall and ratio of number of landfall with the total number of tropical cyclones. All these numbers have been averaged over the 20-member ensemble

Year	Frequency	Landfall	Landfall ratio
2000	10	2	0.20
1998	5	0	0

Table 3: Observed tropical statistics

The frequency of tropical cyclones varies greatly from one experiment to the other. In EXP2000, the frequency of tropical storms is about twice as large as in EXP1998, as observed. A Wilcoxon-Mann-Whitney test (WMW test; see, e.g. Wonnacott and Wonnacott 1977) applied to the 20-member ensemble indicates a significance exceeding 99% in the difference. EXP2000_PAC simulates significantly more tropical storms than all other experiments (significance larger than 99%). Since the only difference between EXP2000_Pac and EXP1998 is the tropical Pacific SSTs, this suggests that tropical Pacific SSTs have a significant impact on the frequency of SIO tropical storms. This is probably due to the fact that Pacific SSTs impact the vertical wind shear over the SIO. La-Niña conditions over the tropical Pacific reduce the vertical wind shear over the SIO in EXP2000_Pac, which creates more favorable conditions for tropical cyclone genesis. EXP2000_PAC simulates about twice as many tropical storms as EXP2000, although both experiments have the same SST forcing over the tropical Pacific. This is likely due to the warmer SSTs over the SIO in EXP2000_PAC than in EXP2000. The difference in local SSTs between these two experiments exceeds 2K over most of the SIO, which is large enough to impact the frequency of tropical cyclones (see Section 2). This is also confirmed by the very low number of tropical cyclones in EXP1998_PAC, with cold SSTs over the SIO and El-Niño conditions over the tropical Pacific. Both conditions are conducive to less tropical cyclone activity over the SIO. This result confirms the dual impact of ENSO on tropical cyclone frequency over the SIO proposed in Section 2. El-Niño conditions are conducive to an increase of vertical wind shear over the SIO due to teleconnections originating from the tropical Pacific SST anomalies and to warmer SSTs over the SIO. The increase of vertical wind shear is conducive to less SIO tropical cyclones, whereas the increase of SIO SSTs is conducive to more tropical cyclones. These impacts are of opposite sign, and this may explain why the interannual frequency of tropical cyclone over the SIO is poorly correlated with ENSO.

b) Tropical storm mean genesis location

The tropical mean genesis location is defined as the first position of detected tropical cyclones averaged over the complete 3 months of integration. This has been calculated for each member of the 20-member ensembles. Using a WMW test, no significant difference was found between EXP2000, EXP1998 and EXP2000_PAC. However, in EXP1998_PAC, the mean genesis location is significantly more north -eastward than in the other experiments. The strong zonal mean flow and colder SST conditions in EXP1998_PAC, seems to have almost completely suppressed the tropical storm activity in higher latitudes and in the western part of the basin.

c) Tropical storm intensity

As for tropical storm mean genesis location, the mean intensity of tropical storms (defined as the maximum wind velocity during the whole trajectory of the cyclone) has been averaged over all the cyclones that develop during the 3 months of integrations. The WMW test detects a significant difference between the 4 ensemble experiments. In EXP2000_PAC the tropical cyclones are significantly more intense than in EXP2000, EXP1998 and EXP1998_PAC, whereas EXP1998_PAC produces tropical cyclones significantly weaker than in the other experiments. There is no significant difference between EXP1998 and EXP2000.

d) Tropical storm tracks

The tropical cyclone tracks vary significantly from EXP2000 to EXP1998 (Fig. 7). Tropical cyclones in EXP1998 tend to recurve or die east of Madagascar, whereas tropical cyclones in EXP2000 tend to cross Madagascar and sometimes make a landfall over Mozambique. Figures 8a and 8b display the distribution of tropical cyclone days in EXP1998 and EXP2000 after normalization by the total number of tropical cyclone days over the entire basin simulated by each experiment. Figure 8c displays the difference between the two experiments. EXP2000 displays more tropical cyclone activity west of Madagascar, but less activity east of Madagascar. The WMW test applied to the ensemble distribution of the number of tropical cyclone days averaged over the region west of Madagascar (30E-50E, 25S-15S) indicates that the difference between EXP1998 and EXP2000 is significant at a level of confidence exceeding 95%. The same test applied to the region east of Madagascar (50E-60E, 15S-25S) indicates that the difference in that region is significant with a level of confidence exceeding 95%. This result demonstrates that in the model, the SST forcing has a significant impact on the tropical cyclone tracks. This impact is consistent with observations (Fig. 3).

EXP2000_Pac exhibits similar tracks to EXP2000, whereas EXP1998_Pac exhibits tracks consistent with the

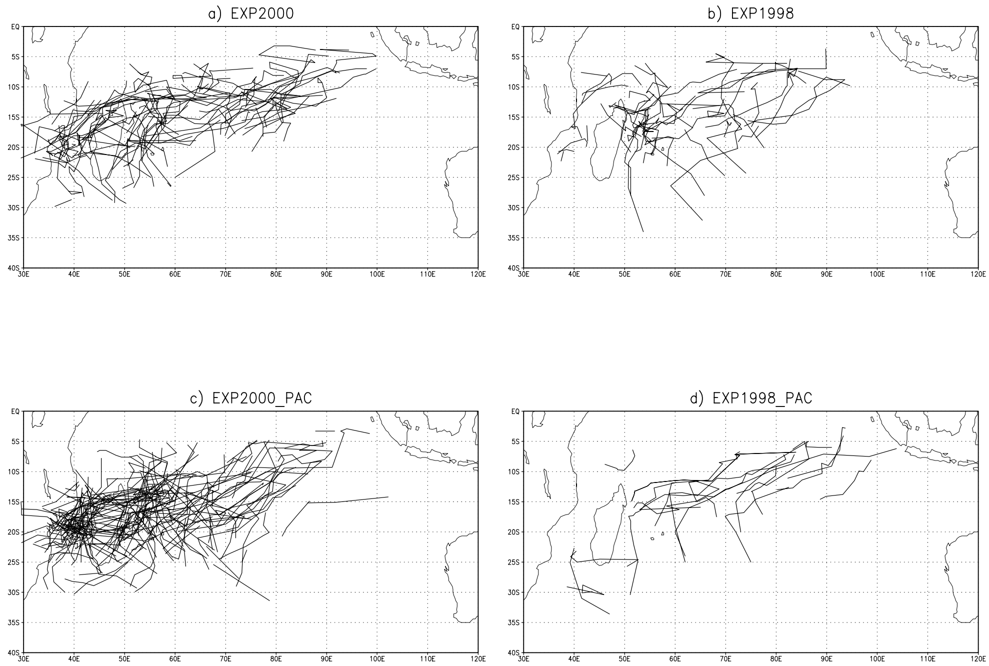

Figure 7: Tropical storm tracks simulated by the 20-member ensemble of a) EXP2000, b) EXP1998, c) EXP2000_Pac and d) EXP1998_Pac. This figure shows a significant impact of the SST forcing on the simulated tropical cyclone distribution. The tropical cyclone activity west of Madagascar is significantly larger in EXP2000 and EXP2000_Pac than in EXP1998 and EXP1998_Pac.

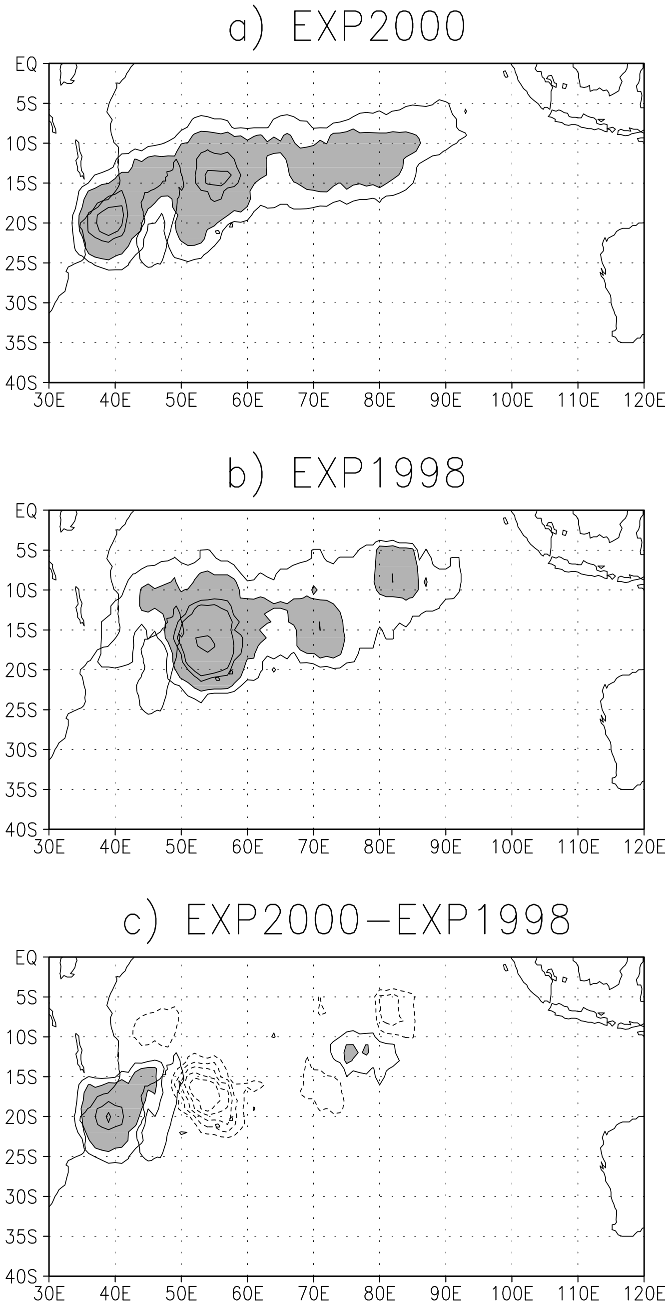

Figure 8: Distribution of tropical storm days simulated a) by EXP2000 and b) EXP1998 and c) the difference of EXP2000 and EXP1998. Over each grid point, the number of tropical cyclone days has been normalized by the total number of tropical storm days simulated by each experiment over the entire SIO. The first contour is 0.02, and areas where the value exceeds 0.04 are shaded. This figure shows that tropical cyclones have significantly different tracks in EXP2000 than in EXP1998, consistent with observations in Figure 3.

tracks in EXP1998. Figures 9a and 9b display the distribution of tropical cyclone days in EXP2000_Pac and EXP1998. The difference between EXP2000_Pac and EXP1998 (Fig 9c) is consistent with the difference in tropical cyclone days between EXP2000 and EXP1998 (fig. 8c). The WMW test also shows that this difference is significant. Since the only difference between EXP1998 and EXP2000_Pac is the SST forcing over the tropical Pacific, this result demonstrates that the difference in tracks between EXP1998 and EXP2000 is essentially due to the remote impact of tropical Pacific SSTs.

e) Tropical cyclone landfall

According to the previous paragraphs, the tropical Pacific SSTs have a significant impact on the statistics of tropical cyclones over the SIO. One would expect that these differences have significant consequences on the risk of landfall over Mozambique. The number of tropical cyclone landfalls over Mozambique has been counted for the 4 sets of experiments and the results are displayed in Table 2. When forced by SSTs of 2000 (EXP2000), 14 of the 20 atmospheric AGCM integrations simulate a landfall over Mozambique, whereas only one member of the ensemble simulates a landfall when forced by SSTs of 1998 (EXP1998). Applying simple binomial statistics suggests that the probability of getting such a difference in the total number of tropical cyclone landfalls by chance is less than 0.5%. In EXP2000 the proportion of landfalling storms is 19%, which is close to the observed one (Table 3). In EXP1998, the percentage of tropical cyclones with a landfall over Mozambique is just 2%. Therefore, the difference in the probability of landfall seems to be significant. This demonstrates that the risk of landfall over Mozambique in the model is affected by SSTs. Thus the results obtained with the model look consistent with observations, supporting the conclusions of Section2.

The difference between EXP2000_Pac and EXP1998 is even more striking, with 26 landfalls in EXP2000_Pac and just one in EXP1998. The only difference between the two experiments is the tropical Pacific SSTs. This demonstrates that the Tropical Pacific SSTs have a significant impact on the risk of landfall over Mozambique. This is also found to be true when comparing EXP2000 and EXP1998_PAC, experiments which differ only in the tropical Pacific SSTs.

The significant difference in the risk of landfall is partially due to a difference in the frequency of tropical cyclones. For instance, EXP2000_PAC simulates twice as many tropical cyclones as EXP2000 with a significant increase in the frequency of landfall over Mozambique. This can be explained by warmer SSTs over the SIO in EXP2000_PAC, as will be demonstrated in the following section. Interestingly, the fractions of tropical cyclone landfall in EXP2000 and EXP2000_PAC are very close, near 20% (Table 2).

3.3 Impact of local SSTs

In order to evaluate the impact of local SSTs, the SIO SSTs have been warmed and cooled by 0.5K over the main tropical cyclone development region in SIO (30E-110E, 10S-25S). The choice of 0.5K was made because it is close to the amplitude of the standard deviation of SSTs over the SIO in La Niña years. 20-member integrations of the AGCM forced by the modified SSTs (EXP2000_SIN+0.5 and EXP2000_SIN-0.5) have been compared to EXP2000. Table 4 describes the setting of the two experiments. EXP2000_SIN+0.5 simulates significantly more tropical cyclones (103 events instead of 73) than the control experiment EXP2000 with a confidence level greater than 95%. The number of landfalls is slightly higher (19 instead of 14), but the percentage of tropical cyclones with landfall is about the same in both experiments (Table 5). On the other hand, cooling SIO SSTs by 0.5K reduces the number of landfalls to 7 (instead of 14), which is significantly less than in EXP2000_SIN+0.5 (significance larger than 90%), although the total number of tropical cyclones is not significantly reduced compared to EXP2000. The tracks are not significantly different between the 3 ensemble-integrations (see Fig. 10). However, tropical cyclones are significantly less intense in EXP2000_SIN-0.5, and as a consequence have a shorter duration. This may explain why the percentage of tropical cyclones with a

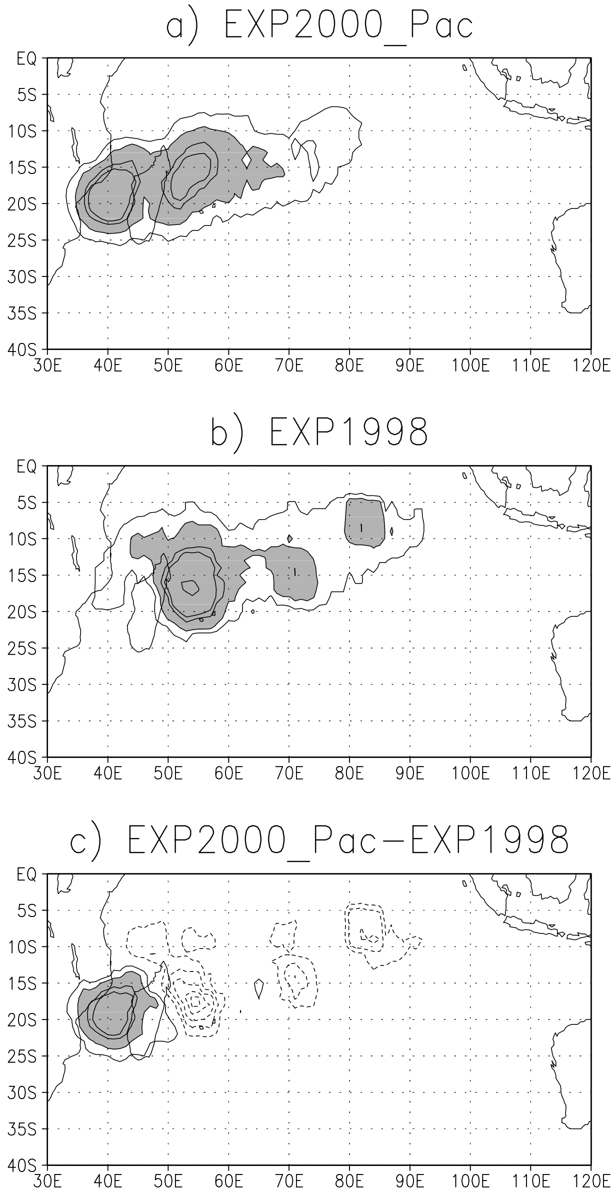

Figure 9: Same as Figure 8, but for EXP2000_Pac instead of EXP2000. The difference between EXP2000_Pac and EXP1998 is consistent with the difference between EXP2000 and EXP 19998 in Fig 8.c

landfall over Mozambique in EXP2000_SIN-0.5 is only half that in EXP2000.

Experiment	SSTs over the SIO	SSTs everywhere else
EXP2000	1999/2000	1999/2000
EXP2000_SIN+0.5	1999/2000+0.5K	1999/2000
EXP2000_SIN-0.5	1999/2000-0.5K	1999/2000

Table 4: Description of the settings of EXP2000, EXP2000_SIN+0.5,EXP2000_SIN-0.5

Experiment	Frequency	Landfall	Landfall ratio
EXP2000	3.65	0.7	0.19
EXP2000_SIN+0.5	5.35	0.95	0.18
EXP2000_SIN-0.5	3.4	0.35	0.10

Table 5: Same as Table 2 but for the experiments described in Table 4.

3.4 Conclusion of the sensitivity experiments

The sensitivity experiments described in this section suggest that tropical Pacific SSTs have a significant impact on the risk of landfall over Mozambique, through their impact on the large-scale circulation. Model tropical storms tend to have a more zonal track during the 2000 La-Niña season than during the 1998 El-Niño season. The experiments also suggest that SIO SSTs impact the risk of landfall through their impact on the intensity and duration of model tropical cyclones. These results are consistent with the observational analysis presented in Section 2. From these sensitivity experiments, it can be concluded that an AGCM can simulate the impact of SSTs on the risk of landfall over Mozambique. This is an important first step for the seasonal forecasting of the risk of landfall, since these results suggest that if we can predict the SSTs a few months in advance, then the AGCM should be able to predict the risk of landfall over Mozambique. All the experiments described in the present section were forced by observed SSTs. The next step consists of using a coupled ocean-atmosphere GCM, which will predict SSTs and their impact on the risk of landfall over Mozambique.

4 Seasonal forecasting of the risk of landfall over Mozambique

4.1 Operational seasonal forecasting system at ECMWF

A dynamical seasonal forecasting system has been set up at ECMWF (Stockdale et al 1998), based on coupled GCM integrations. The atmospheric model component is IFS cycle 15r8 with a resolution of T63 corresponding to a grid resolution of 1.875^o with 31 vertical levels. The ocean resolution is roughly comparable, but in the tropics increases to 0.5^o in the latitudinal direction, so as to resolve the equatorial waves, which are important for El-Niño. The atmospheric and land surface initial conditions are taken from the operational analysis produced by ECMWF. Ocean initial conditions are taken from an analysis of the ocean state made by using the forced response of the ocean to wind stress, heat flux and fresh water forcing, and assimilating sea surface temperature analyses of the ocean and all available sub-surface thermal ocean data. The atmosphere and ocean are coupled without flux correction and integrated forward for 6 months from the initial conditions. About 30 integrations are made each month, one from each day's ocean and atmospheric analysis. This ensemble is referred to as the forecast ensemble. Errors in the component models lead to a drift in the climate of the coupled system. Therefore, it is necessary to calibrate the forecasts with the climatology of the coupled GCM.

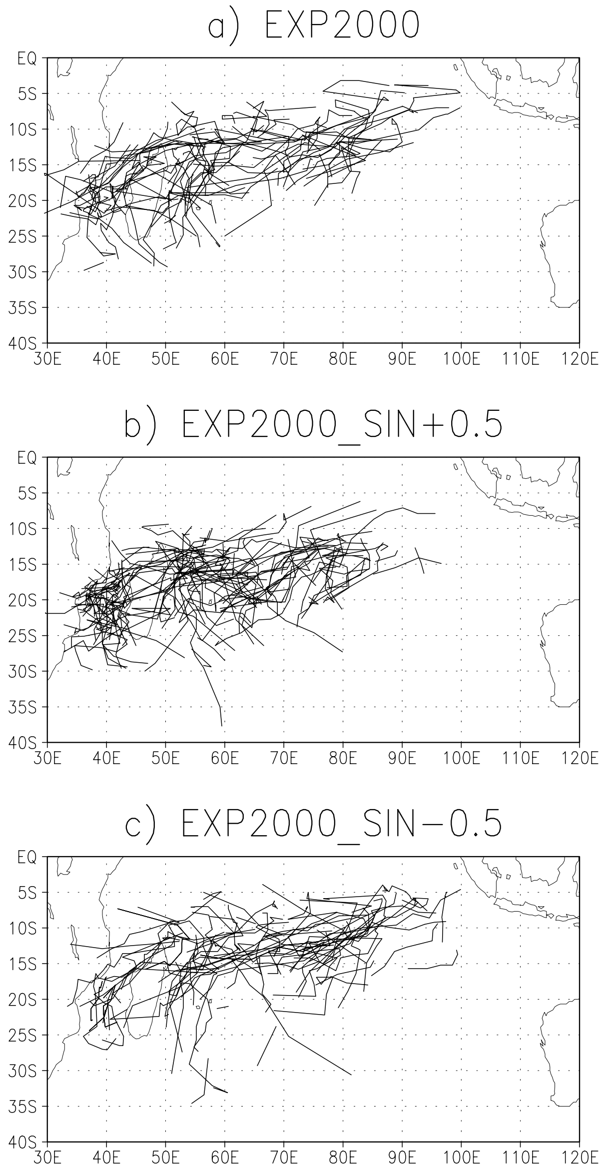

Figure 10: Tropical cyclone tracks simulated by a 10-member ensemble of a) EXP2000, b) EXP2000_SIN+0.5 and c) EXP2000_SIN-0.5. This figure shows that the all 3 experiment do not display significant difference in tropical cyclone tracks. However, EXP2000_SIN+0.5 seems to produce significantly more tropical cyclone activity, whereas EXP2000_SIN-0.5 seems to produce less tropical cyclone activity than EXP2000.

To estimate the climatology of the coupled system, a set of 11 integrations has been made each month from an earlier period (1991 to 1996). This creates a total ensemble of 66 members, which will henceforth be referred to as the climatological ensemble for each calendar month.

In the present section, for clarity, only the forecasts starting between 16 October and 15 November are considered, but results are about the same with the forecasts issued one month before or one month later. The first month of a forecast is discarded, and the tropical cyclone activity from 1st December to 30 April is considered. The total period of forecasts (starting dates from 1991 to 2000) is not enough to fully estimate the skill of the coupled GCM, but it is probably sufficient to give a general idea of the behavior of the seasonal forecasting system.

The horizontal resolution of the atmospheric component of the coupled GCM is too coarse to allow meaningful statistics about tropical cyclone landfall to be developed. At such low-resolution, tropical cyclone tracks are too poleward, which may be a consequence of their too large size (Vitart et al 1997), and they disappear too quickly (not shown). Therefore a landfall over Mozambique is an extremely unlikely event in the model. This however does not necessarily mean that seasonal forecast of risk of tropical cyclone landfall over Mozambique cannot be issued with this model. As underlined in the previous sections, there are large-scale predictors for the risk of landfall over Mozambique. Local SSTs and tropical Pacific SSTs significantly impact the risk of landfall. If the coupled model can produce skillful forecasts of these two factors, then it should be possible to deduce what the risk of landfall would be during the coming tropical cyclone season.

4.1.1 Large-scale parameters

The ECMWF seasonal forecasting system displays skill in forecasting SST anomalies over the NINO3.4 region averaged from 1st January to 30 April with a linear correlation of 0.95 (99.9% significance) between predicted SSTs and observations. Of particular relevance for this paper, the system was successful in predicting the persistence of La-Niña conditions during the 2000 tropical cyclone season, although there is a considerable spread in the amplitude of the predicted La-Niña.

As discussed in previous sections, tropical Pacific SST impacts the tracks of tropical cyclones through its impact on the zonal steering flow. The coupled model displays strong skill in predicting the interannual variability of the zonal steering flow over the SIO (not shown), although, in the mean, the model tends to forecast too strong a zonal steering flow over the SIO, particularly during El-Niño years. The linear correlation between the interannual variability of the mean of the ensemble and the NCEP reanalysis for the same period is 0.83 (95.4% significance).

Another important predictor of the risk of landfall over Mozambique is the South Indian Ocean SSTs. The linear correlation between the predicted SSTS and averaged over the region (30W-105W, 25S-10S) from 1st January to 30 April with observations is 0.84 (99.6% significance). In particular, the model was successful in predicting that SST anomalies over the Central SIO would be warmer during the first quarter of 2000 than for the corresponding period of 1999.

In summary, the model displays skill in forecasting the main large-scale factors that affect the risk of landfall over Mozambique, and in particular, the intense 2000 tropical cyclone season over the SIO. This suggests that low-resolution dynamical models can be useful in helping to predict the risk of landfall over Mozambique, by predicting the main large-scale factors that favor the occurrence of tropical cyclone landfall over Mozambique.

4.1.2 Tropical storm statistics

Over the SIO, the climatological frequency of model tropical cyclones is about 20% less than observed. Surprisingly, the operational system creates more model tropical storms than the sensitivity experiments of Section 3 which have a higher horizontal resolution (TL159 instead of T63). However, the atmospheric components are not the same: IFS cycle 23r4 is used in the sensitivity experiments, whereas IFS cycle 15r8 is used in the operational seasonal forecasting system. The difference in physical parameterization between both cycles may explain the difference in tropical storm climatology. The ECMWF seasonal forecasting system has poor skill in predicting the interannual variability of tropical storm frequency over the SIO (Vitart and Stockdale 2001), with a linear correlation between observed and predicted tropical cyclone frequency of only 0.4 for the verification period 1992-2001. However, the model displays more skill in predicting the interannual variability of intense tropical cyclones, with a linear correlation of 0.7 (96% significance). The observed 2000 season was more active with 13 tropical cyclones, including 8 intense (with hurricane intensity) tropical cyclones during the period 1st December to 30 April, when the average number of tropical cyclones from the verification period 1992 to 1997 was ten, including 5 intense tropical cyclones. The observed frequency of tropical cyclones during the 1999 season was close to climatology, though the frequency of intense tropical cyclones was exceptionally low (only 3 tropical cyclones reached hurricane intensity). The observed 1998 tropical cyclone season with El-Niño conditions was close to normal. The coupled GCM predicted an increase of intense SIO tropical cyclone activity in 2000 with a significance greater than 95% and a significant reduction of intense tropical cyclone activity in 1999 with similar significance (Table 6). The dynamical model also predicted normal activity for 1998. The model forecasts are consistent with observations although the coupled GCM displays less interannual variance of intense tropical cyclone frequency than observations (Table 6).

	Observations	Ensemble mean
2000	8	7
1999	3	4
1998	5	5
Climatology	6(2)	6(0.5)

Table 6: Observed and predicted number of intense tropical cyclones (maximum sustained wind exceeding 32 m/s) . The number in parenthesis represents the standard deviation. The climatology corresponds to the period 1991-1996.

According to observations, observed tropical cyclones have a more zonal track than climatology during both 1999 and 2000 La-Niña seasons, and a more poleward track during the El Niño season of 1998. Although model tropical cyclones tend to have a track more poleward than observations, the model tropical cyclone tracks for 1999 and 2000 are more zonal than model climatology (not shown), as observed. In particular, the model predicts more tropical cyclone activity over the Mozambique Channel in 2000 than in 1998 (Fig. 11). In 1999, the map of tropical cyclone days is similar to that in 2000, but with less intensity (Fig 11b). This is consistent with the lower topical cyclone activity in 1999 than in 2000 described in the previous paragraph.

In summary, the operational seasonal forecasting system cannot predict explicitly the risk of landfall over Mozambique with such a low resolution. However, the risk of landfall could be inferred by forecasting the main factors affecting the tropical storm activity over the SIO: ENSO and local SSTs. The risk of landfall over Mozambique can also be deduced from the general statistics of tropical cyclones over the SIO. For instance, the model predicted in November 1999 that the tropical storm activity of the 2000 SIO season would be higher than climatology with more activity west of Madagascar. From this forecast, it could be deduced that the probability of landfall over Mozambique during the 2000 tropical cyclone season would be increased.

Following the success of the low-resolution coupled model, it is likely that if the model had a sufficiently high resolution, it would be able to predict explicitly the risk of landfall over Mozambique. The next section

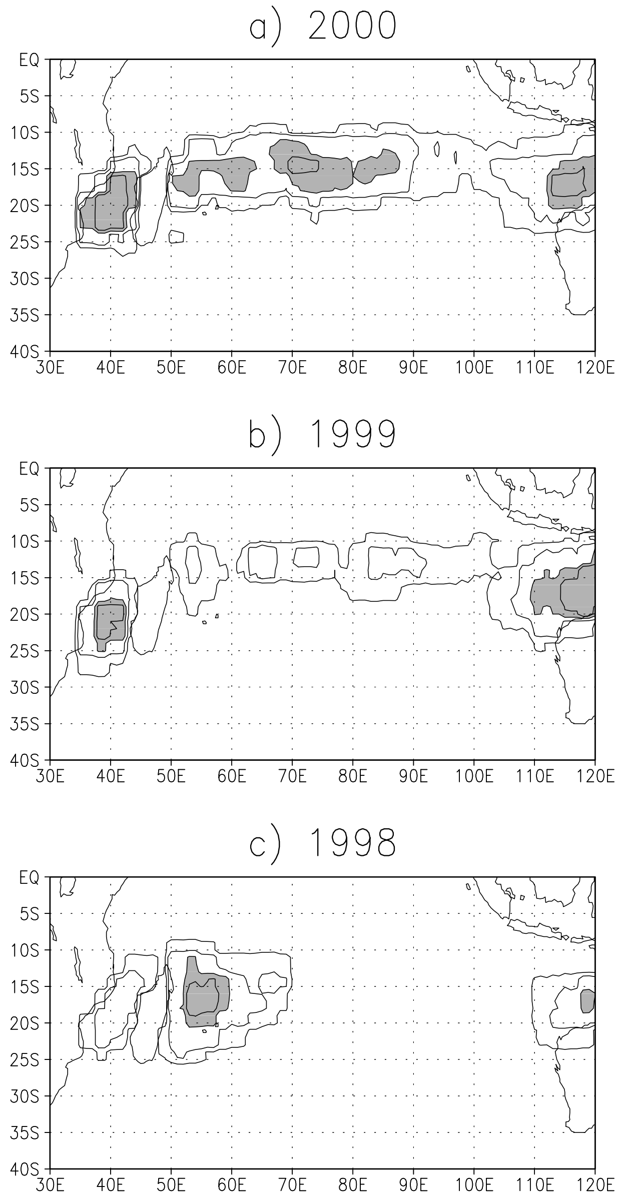

Figure 11: Distribution of tropical cyclone days per season predicted by the 30-member ensemble of the ECMWF operational seasonal forecast for a) the 2000, b) the 1999 and c) the 1998 tropical cyclone seasons (defined from 1st December to 30 April). The forecasts start one day apart from 15 October to 15 November, and the length of integration is 6 months. The horizontal resolution of the atmospheric model is T63. The minimum level is 1 tropical cyclone day, and areas where the number of tropical storm days exceeds 4 are shaded.

investigates if this is the case by integrating a coupled GCM for 3 months starting on 1st January with the same high horizontal resolution as used for the sensitivity experiments.

4.2 Hindcasts using the ECMWF coupled model with a high-resolution atmospheric model.

In order to evaluate the skill of a coupled GCM to predict explicitly the risk of landfall over Mozambique, a 10-member ensemble of coupled ocean-atmosphere integrations has been generated from 1987 to 2001. The atmospheric model is IFS cycle 23R4 with a horizontal resolution of TL159 with 40 vertical levels. According to the sensitivity studies in Section 3, this resolution should be enough to allow the explicit forecast of tropical cyclone landfalls. The length of integration is 3 months, and in order to remove the most deterministic part of the forecast, the first 10 days of integrations have been removed. All the forecasts start on 1st January, for each year from 1987 to 2001 (15 years). The atmospheric initial conditions have been perturbed using singular vectors (Palmer et al, 1998) and stochastic perturbations are applied during the integrations to the physics tendencies (Palmer 2001). Oceanic initial conditions are perturbed in two ways: random perturbations are applied to the wind stress during the data assimilation in order to produce 5 different realizations of the ocean state. Random perturbations are also applied to the SSTs in order to produce a 10-member ensemble.

The objective procedure for tracking model tropical cyclones described in Section 3 has been applied to each member of the ensemble form 1987 to 2001. The mean number of tropical cyclones in the period from 11 Januray to 31 March is 4.6, which is lower than the observed mean number of tropical cyclones over the same period of time (7.5). This is likely to originate from the atmospheric component of the coupled GCM, since the AGCM used for the sensitivity experiments described above displays the same bias in the frequency of SIO tropical cyclones.

The frequency of predicted SIO tropical cyclones displays an interannual variability that is positively and significantly correlated with the observed interannual variability (correlation of 0.55 between the mean of the ensemble and observations), although the model fails to predict the exceptionally strong number of SIO tropical cyclones in 1994. The interannual variability predicted by the higher resolution forecast discussed here is more realistic than the one predicted by the operational seasonal forecasting system (Vitart and Stockdale, 2001).

The coupled model predicts a significant interannual variability in tropical cyclone tracks. Figure 12 shows an example of such strong interannual variability. In panel a, the tracks of all the tropical cyclones generated by 10-member ensemble integrations of the coupled GCM starting on 1st January 2000 are displayed. They look consistent with observations (Fig 1.a). A couple of model tropical cyclones have a westward trajectory and landfall over Mozambique as did Leon-Eline and Hudah, although their genesis location is in the central part of the SIO instead of the eastern edge of the basin. Panel b shows the predicted trajectories of the ensemble forecasts starting on 1st January 1998. As in observations, most of the tropical cyclone activity is concentrated just east of Madagascar with few tropical cyclones crossing the island.

The number of landfalls over Mozambique has been counted for each member of the ensemble. The mean number of landfalls (averaged over the 10 members of the ensemble) has been calculated for each year from 1987 to 2001. As the model simulates fewer tropical cyclones than observed by a factor of 1.5, the number of landfalls per year and per ensemble member has been multiplied by 1.5. The interannual variability of the predicted number of landfalls is significantly correlated to the predicted interannual variability of NINO3.4 SSTs (correlation of 0.7). The 4 El-Niño years (1987, 1992, 1995 and 1998) correspond to 4 of the years where the model predicts the lowest risk of landfall over Mozambique (Fig. 13). The coupled model predicts a risk of landfall over Mozambique above average during 3 of the 4 La-Niña years (1996, 1999 and 2000), but not in 1989 (Fig. 13). Therefore, the impact of ENSO on the risk of landfall over Mozambique, discussed in Sections

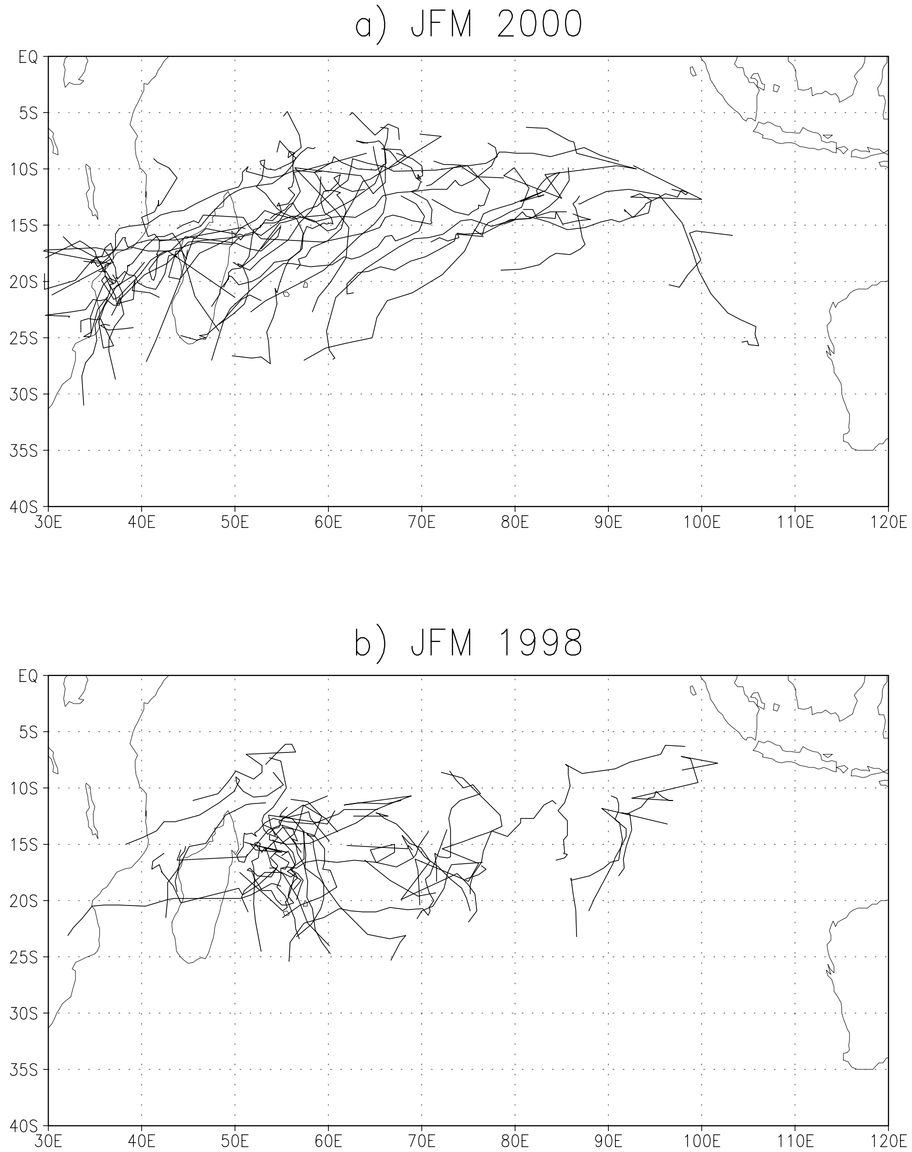

Figure 12: Tracks predicted by the 10-member ensemble during the 3 months of integration when starting a) from 1st January 2000 and b) from 1st January 1998. This graphic suggests a significant interannual variability in the tracks of the tropical cyclones predicted by the coupled GCM.

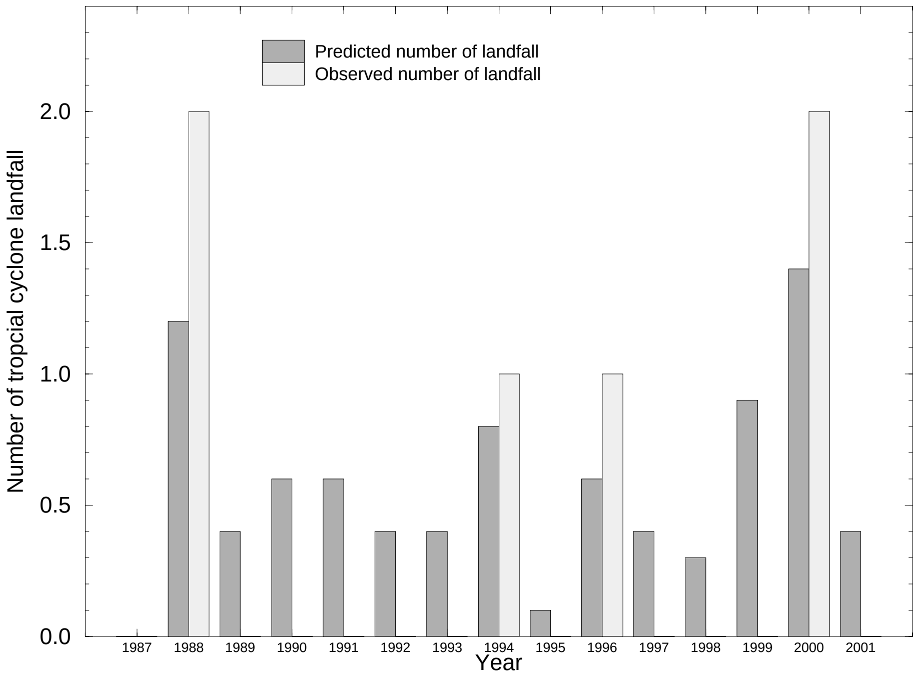

Figure 13: Interannual variability of the observed and predicted number of tropical storm landfall over Mozambique. The predicted number of tropical storm landfall has been calculated by taking the mean of the ensemble distribution, and multiplying it by 1.5, since the model simulates 1.5 less tropical cyclones than observed.

1 and 2 seems to be present in the forecast.

During the 15 years of the hindcast, Mozambique has been hit by tropical cyclones in four years (1988, 1994, 1996 and 2000). Interestingly, the model predicts a high risk of landfall during these four years. All the years where the model predicts a reduced risk of landfall coincide with years with non-observed landfall over Mozambique. There are 3 years when the model predicted a high risk of landfall but no tropical cyclone landfall was observed (1990, 1991 and 1999). However, the seasonal forecasts are probabilistic forecasts, not deterministic. An increased risk of landfall does not necessarily mean that there will be a landfall over Mozambique, especially when the predicted number of landfalls is less than 1. The model successfully predicts a high risk of landfall over Mozambique for the 2000 season, higher than in any other year. Interestingly, it also predicts a high risk of landfall in 1988 and 1994, which are not La-Niña years. Both 1988 and 1994 seasons displayed a tropical cyclone landfall over Mozambique. Therefore, it seems that although ENSO has a significant impact on the predicted risk of landfall, other factors, such as local SST patterns, may play a significant role. The predicted high risk of landfall over Mozambique in 1988 and 1994 suggests that the model is able to predict the impact of these additional factors on the risk of landfall over Mozambique. The predicted interannual variability of tropical cyclone landfall is positively and significantly correlated with the observed interannual variability (correlation of 0.81 with a level of confidence of 99%). In summary, this hindcast experiment strongly suggests that the high-resolution coupled system has skill in predicting the number of landfalls over Mozambique.

5 Conclusion and discussion

The 2000 tropical cyclone season over the South Indian Ocean was exceptional in terms of landfalls over Mozambique. The present paper shows that a coupled GCM with sufficiently high horizontal resolution has skill in predicting the risk of landfall over Mozambique. More especially, the coupled model predicts a number of landfalls for the 2000 tropical cyclone season that is higher than in any of the previous 14 years. This result gives a strong indication that the risk of landfall over Mozambique can be predicted, and that coupled GCM integrations could be a useful tool for predicting such risk. At present, operational seasonal forecasting systems are using horizontal resolutions that are too coarse to properly resolve the trajectory of tropical cyclones. However, the study of the tropical cyclone tracks predicted by the ECMWF operational seasonal forecasting system, indicates that although the model has no skill in explicitly predicting landfalls over Mozambique, it has skill in predicting the interannual variability of the tropical cyclone tracks, and to a lesser extent intense tropical storm frequency. Therefore, current seasonal forecasting systems could be used for operational prediction of the risk of landfall over Mozambique, by predicting tropical cyclone statistics that have an impact on the probability of a landfall. The T159 horizontal resolution that was used for the sensitivity studies (Section 3) and the 1987-2001 hindcast (Section 4.2) seems fine enough to allow the explicit prediction of tropical cyclone landfalling. Such a high atmospheric resolution is likely to be used for operational seasonal forecasting in the coming years. Therefore, there is hope that in the near future, operational dynamical seasonal forecasting systems will be able to explicitly predict the risk of landfall over Mozambique.

Obervational studies of Section 2 suggest that two factors significantly impact the risk of landfall over Mozambique: ENSO and SIO SSTs. Sensitivity tests in Section 3 using an AGCM reproduce this impact and therefore confirm the importance of ENSO and SIO SSTs on the risk of landfall over Mozambique. This demonstrates that an AGCM can be a very useful tool in order to quantify how the variability in the large-scale circulation impacts the statistics of tropical cyclones. It can also be concluded from the observational study and the sensitivity experiments that the skill of a dynamical model in predicting the risk of landfall over Mozambique depends strongly on its skill in predicting SSTs over the SIO and tropical Pacific.

The present study focuses on the South Indian Ocean and the risk of landfall over Mozambique prompted by the exceptional 2000 tropical cyclone season and its catastrophic consequences for Mozambique. Future plans include investigating if a coupled model could also be useful in predicting the risk of landfall over other areas. It may be possible to predict the risk of landfall over several basins such as the North Indian Ocean, the western North Pacific, the eastern North Pacific, where there is significant interannual variability of tropical cyclone statistics. For that purpose, additional GCM integrations will be needed, since the tropical cyclones seasons over these basins differ from the SIO tropical cyclone season.

The North Indian Ocean is a relatively small basin, so that the majority of tropical cyclones make a landfall. Therefore, the risk of landfall over the North Indian Ocean is likely to be strongly correlated with the frequency of tropical cyclones over this basin. 1992 was a catastrophic year in terms of landfall over India and Bangladesh, and coincides with the highest number of tropical cyclones on record (12 cyclones, 3 times more than the annual average). Predicting the frequency over the North Indian Ocean is likely to be a key element for predicting the risk of landfall over this basin. However, numerical models so far have not been successful in predicting a realistic interannual variability of tropical cyclones over this basin (Vitart et al, 1997; Vitart and Stockdale, 2001). It is likely that the Madden Julian Oscillation plays an important role in the frequency of tropical cyclones over this basin, and numerical models are generally unsuccessful in simulating a realistic MJO (Slingo et al 1996).

Over the western Pacific and eastern Pacific, tropical storm genesis location and tracks vary significantly from one year to another due mostly to the impact of ENSO (Chan, 1985). Models have skill in simulating the interannual of tropical cyclone mean genesis location over the North Pacific (Vitart et al 1998, Vitart and

Stockdale 2001). Therefore if an AGCM is able to simulate realistic tracks of tropical cyclones over this basin, it is possible that this system may have skill in simulating the risk of landfall over China, Japan or the western coast of Mexico.

Over the North Atlantic, ENSO seems to have a significant impact on the risk of landfall over the United States. Richards and O'Brien(1996) and Bove et al (1998) found that the probability of at least one landfall is significantly reduced during an El-Niño event. Vitart and Stockdale (2001) have shown that the ECMWF operational seasonal forecasting system has skill in predicting the interannual variability of tropical storms over the Atlantic, and most especially the significant reduction of tropical storm activity due to El-Niño. However, as for the SIO basin, the simulated tropical storm tracks are too unrealistic at such low resolution to allow the prediction of tropical cyclones over the US with this operational system.

In summary, the results obtained for the South Indian Ocean are encouraging, and suggest that coupled GCMs may be a useful tool for predicting the risk of landfall over Mozambique. It is likely that the prediction of the risk of landfall could be extended to other basins, but further work is needed to confirm this.

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