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Impact of greenhouse gas concentrations on tropical storms in coupled seasonal forecasts

By FRÉDÉRIC VITART* and FRANCISCO DOBLAS-REYES, *ECMWF, Shinfield Park, Reading RG2 9AX, UK*

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ABSTRACT

The impact of using realistic varying instead of fixed greenhouse gas concentrations is investigated in an ensemble of 6-month integrations of a coupled general circulation model (CGCM) from 1958 to 2001. Results suggest that an increase of greenhouse gas concentration is conducive to a decrease of tropical storm activity over all basins except the western North Atlantic and the eastern North Pacific. This result seems consistent with the impact of an increase of greenhouse gas concentration on the thermodynamical and dynamical variables that have an impact on the tropical cyclone activity.

The interdecadal variability of tropical storm frequency is more realistic when using realistic varying GHG concentration than when using constant GHG. The improvement seems to be due to a more realistic trend of tropical storm frequency than to an improvement of the interdecadal variability around this trend. Therefore, it is important for seasonal forecasting systems to take account of the variation of GHG in the hindcast period used to calibrate the system.

1. Introduction

Several studies (e.g. Broccoli and Manabe, 1990; Haarsma et al., 1993; Bengtsson et al., 1996; Sugi et al., 2002) have evaluated the impact of an increase in greenhouse gas concentration on the frequency of tropical storms by integrating a general circulation model with and without an increase of CO_2. The statistics of the model tropical storms were then compared. Those studies gave contradictory results. For instance, according to Haarsma et al. (1993), the 11-layer United Kingdom meteorological Office (UKMO) atmospheric GCM coupled to a 50-m mixed layer ocean simulates an increase of 50% in the number of tropical storms. On the other hand, Bengtsson et al. (1996) document a significant *reduction* of tropical storm frequency when using the T106 ECHAM3 model. They explained this result by a weakened Hadley circulation in doubling CO_2 scenario. Broccoli and Manabe (1990) noted that their results were crucially dependent on the parameterization of the clouds: when using prescribed clouds, the number of storm-days undergoes a significant increase in the doubled-CO_2 climate while a significant reduction of tropical cyclone activity is detected when using predicted clouds. More recently, Sugi et al. (2002) found that the global frequency of tropical storms simulated by the JMA global model at T106 was significantly reduced in a doubling CO_2 environment. Oouchi et al. (2006) reached the same conclusion using a much finer resolution model (20 km resolution). Another technique for evaluating the impact of an increase of greenhouse gas on the frequency of tropical storms consists in using the seasonal genesis parameter (SGP) (Gray, 1979) to model outputs as a diagnostic for the frequency of tropical storms instead of tracking model tropical storms (Ryan et al., 1992; Royer et al., 1998). Ryan et al. (1992) obtained a near tripling in the number of tropical cyclones with the doubling of atmospheric CO_2 concentration with the CSIRO9 model. In Royer et al. (1998) the application of the SGP to the simulations corresponding to a climate with doubled CO_2 indicates a near doubling of the total number of tropical storms in the Northern Hemisphere. The thermodynamic part of the SGP seems to be responsible for this strong increase of tropical storm activity in agreement with Ryan et al. (1992). By replacing the temperature threshold parameter with a more physically realistic parameter, only a small increase of tropical storm activity is found in the Northern Hemisphere and a small decrease in the Southern Hemisphere (Royer et al., 1998). This result underlines the strong sensitivity to the thermodynamic component of the SGP. Finally, another technique to predict the impact of doubling CO_2 on tropical storm statistics consists in using a regional nested high resolution hurricane model (Knutson and Tuleya, 2004). In this approach, a series of tropical storm case studies from a global circulation model (for both present-day and high CO_2 conditions) are re-run, nesting the storm within the high resolution hurricane model. Results suggest an increase of 3 to 10% in the intensity of the storm

*Corresponding author.
e-mail: Frederic.Vitart@ecmwf.int
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after a century-long build-up of atmospheric CO_2 at 1% per year. They obtain the same result by using highly idealised flow fields along with large-scale time averaged thermodynamic conditions from a global climate model. This method gives an indication of the impact of an increase of greenhouse gas on the intensity of a hurricane, but not on its frequency.

All the studies cited above were based on predicting the statistics of tropical storms in a hypothetical future environment. However, the CO_2 concentration in the atmosphere has increased significantly during the past century, and some of its impact on tropical storms may already be visible. Recent observational studies by Emanuel (2005) and Webster et al. (2005) suggest that the intensity of tropical storms has increase during the past decades because of an increase of greenhouse gas concentration. Webster et al. (2005) also claim that the global number of tropical storms and tropical storm days has decreased in all basins except the North Atlantic during the past decade. However, Landsea (2005) contested the findings of Emanuel (2005) because of discontinuities in the quality of the historical hurricane data and Chan (2005) claimed that the increased typhoon activity in the western Pacific is due to natural decadal variability rather than to an increase of greenhouse gas concentration.

The present paper investigates the possible impact of the increase of greenhouse gas (GHG) during the period 1958–2001 on the statistics of model tropical storms using 6-month long seasonal forecast integrations starting from 1st May and 1st November 1958 to 2001. An advantage of looking at the past fifty years instead of trying to predict future scenarios, as all numerical studies cited above did, is that observations are available, although their reliability before the use of satellites may be questionable. Another advantage of this method is that the technique consisting of tracking model tropical storms has been validated in the context of seasonal forecasting (see Vitart and Stockdale, 2001, for example). Another advantage of this approach is the relatively large set of integrations (the equivalent of about 396 yr of integrations for each experiment).

2. The model experiment

A coupled general circulation model developed at ECMWF has been used in this experiment. The model uses IFS cycle 23R4 and *HOPE_E* as atmospheric and oceanic components (Palmer et al., 2004), respectively. The data consists of sets of 6-month seasonal integrations, each set comprising 88 simulations started from realistic ocean, land and atmosphere initial conditions on the first day of May and November of each year over the period 1958–2001. Each integration consists of an ensemble of nine members at T95 horizontal resolution in the atmosphere. The experiment mimics the setup used to produce ECMWF's operational seasonal forecasts. The initialisation of the integrations followed the method described in Palmer et al. (2004), with the ECMWF reanalysis ERA40 (Uppala et al., 2005) data for the atmosphere and soil initial conditions and a set of ocean runs forced with ERA40 fluxes with wind stress and SST perturbations to generate the ensemble.

Operational seasonal forecasts around the world usually apply a fixed GHG concentration during the simulations. This is not only the case for the forecasts themselves, but also for the set of 20–30 yr of past predictions required for calibration (Doblas-Reyes et al., 2005; Stephenson et al., 2005) and to estimate the forecast quality of the system (Jolliffe and Stephenson, 2003; Hagedorn et al., 2005). The need for long series of past integrations and the noticeable increase in GHG concentrations in the last 50 yr imply that this external forcing might play an important role in seasonal forecasting. A control experiment (CONS henceforth) with concentrations of the greenhouse gases CO_2, N_2O, CH_4, CFC_{11} and CFC_{12} fixed to their 1990 concentrations (353 ppmv, 1.72 ppmv, 310 ppbv, 280 pptv and 484 pptv, respectively) was performed. A similar experiment was carried out with concentrations updated every year (VARI). The yearly values of GHG concentrations were taken from IPCC until 2000 and then completed beyond that year with the SRES scenario A1B. A linear regression was applied to the mean annual values, assumed to be a representation of mid-year conditions. No seasonal cycle was used.

An objective procedure for detecting model tropical storms has been applied to the coupled models to track low pressure systems with a warm core between 500 and 200 hPa (see Vitart et al., 1997, for more details). The parameters have been tuned so that the objective procedure detects as many observed tropical storms as possible and as few non-tropical storms as possible when applied to ERA40 interpolated to the same grid as the model. In this approach, model biases and deficiencies will affect the statistics of the tropical storms detected, but this method ensures that the tropical storms detected share exactly the same characteristics as the tropical storms in ERA40.

3. Tropical storm statistics for the periods 1958–1970 and 1989–2001

In the present paper the statistics of tropical storms have been calculated over the following seven ocean basins: South Indian Ocean (SIO) 30–105E, Australian basin (AUS) 105E–165E; South Pacific (SPAC) 165E–110W; North Indian Ocean (NIO) 45E–100E; western North Pacific (WNP) 100E–160W; eastern North Pacific (ENP) 160W–100W (west of the American coast); Atlantic (ATL) 100W-0, east of the American coast. All latitude boundaries are along the equator and 40°N or 40°S.

The objective method for tracking model tropical storms has been applied to the 6-month long seasonal integrations of CONST and VARI. In this section, we compare the statistics of the tropical storms for the periods 1958–1970 and 1989–2001. The period 1958–1970 was chosen because it is sufficiently long to allow a comparison of tropical storm statistics between both integrations, and this period displays the biggest difference in GHG concentration between CONST and VARI (Fig. 1). The

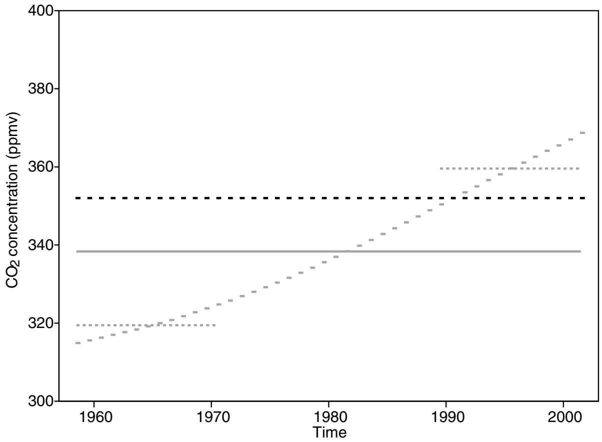

Fig. 1. Greenhouse gas concentration in CONST (dashed black line) and VARI (dotted grey line). In both curves each segment represents the value of the GHG concentration during the 6-month integration. This shows that the GHG concentration is fixed during the 6-month integrations (no seasonal cycle). The dotted grey lines represent the mean greenhouse gas concentration in VARI for the periods 1958–1970 (lower GHG concentration in VARI than in CONST) and 1989–2001 (higher GHG concentration in VARI than in CONST) and the solid grey line represents the mean GHG concentration in VARI during the full period (1958–2001).

second period (1989–2001) has been chosen because the difference in GHG concentration between CONST and VARI is of opposite sign to that in the 1958–1970 period (Fig. 1).

3.1. *Frequency*

The number of tropical storms has been counted for each basin, and each ensemble member for the period 1958–1970. Table 1 displays the climatological number of tropical storms over each ocean basin in CONST and VARI averaged over the 9 ensemble members. CONST and VARI simulate globally about half as many tropical storms as observed (about 90 tropical storms have been observed each year over the period 1958–1970, whereas CONST and VARI generate about 42 tropical storms per year). Camargo et al. (2005) also found a significant underestimation in the total number of tropical storms in all the three atmospheric models forced by observed SSTs they used to simulate the interannual variability of tropical storms. CONST and VARI underestimate the number of tropical storms in all the basins, but the amplitude of the bias varies from basin to basin, as mentioned also by Camargo et al. (2005). Over the period 1958–1970, CONST and VARI display the smallest bias over the Atlantic and the Australian basin (about 6 model storms compared to 9.6 and 10 observed tropical storms). The largest bias in percent is over the eastern North Pacific (about 4 model storms compared to 12 observed tropical storms per year). Over the western North Pacific, CONST and VARI generate on average less than 12 tropical storms per year compared to 29 observed tropical storms, and about 5 and 2 tropical storms over the South Indian Ocean and the South Pacific compared to respectively 13 and 5.3 observed tropical storms.

Despite this discrepancy in the total number of tropical storms, the model displays some skill in predicting the interannual variability of tropical storm frequency during the period 1987–2001, particularly over the western North Pacific and the South Pacific (Vitart, 2006). Results suggest that the total number of tropical storms is reduced by about 3.9% with constant GHG of 1990 relative to that in VARI during the period 1958–1970. Therefore, the impact of the higher concentration of GHG in CONST relative to VARI seems to be a reduction of tropical storm activity in all basins except the North Atlantic and the eastern North Pacific. A Wilcoxon-Mann-Whitney test (WMW; see, e.g. Wonacott and Wonacott, 1977) has been applied to detect if the 9-member ensemble distribution of CONST is statistically different from the ensemble distribution of VARI. According to Table 1, the difference of tropical storm frequency between VARI and CONST is significant only over the South Indian Ocean (within the 5% level of confidence), with a reduction of 10.3% in the frequency of tropical storms, and is marginally significant (within the 10% level of confidence) globally.

The same comparison between CONST and VARI was made but this time for the period 1989–2001. During this period CONST has a *lower* GHG concentration than VARI. The difference in GHG concentration is smaller than during the period 1958–1970 (Fig. 1). Therefore the impact of the difference of GHG concentration on the frequency of tropical storms is expected to be lower for the period 1989–2001 than during the period 1958–1970. The frequency of storms is slightly different between the two experiments and the difference is not statistically significant within the 10% level of confidence over all the basins. Interestingly, the difference is of opposite sign to that for the period 1958–1970 globally (Table 2) and over individual basin, except for the Australian basin and the eastern North Pacific. This suggests a consistent impact of an increase of GHG concentration on the frequency of model tropical storms in both periods.

3.2. *Tropical storm days*

The number of tropical storms is not always a good measure of the tropical storm activity. For instance, the 2002 Atlantic tropical storm activity was considered below normal, although 12 tropical storms were recorded, which is well above the 1950–2000 climatological frequency. However, a large portion of Atlantic tropical storms in 2002 were very weak tropical storms which did not last more than a couple of days with a maximum wind velocity larger than 17 m s^{-1} and the number of Atlantic tropical storm days that year was well below climatology. A more robust measure of tropical storm activity is the number of tropical storm days instead of the frequency of tropical storms. This

Table 1. Ensemble-mean number of model tropical storms per year over the period 1958–1970 simulated by the experiment VARI (variable GHG) and CONST(constant GHG of 1990). The tropical storms have been detected over seven basins: Atlantic (ATL), Eastern North Pacific (ENP), Western North Pacific (WNP), North Indian Ocean (NIO), South Indian ocean (SIO), Australian Basin (AUS) and South Pacific (SP). The last column represents the difference over all the basins. The last row represents the difference relative to VARI between CONST and VARI in percent. Bold numbers indicate when the difference is statistically significant according to the WMW test within a 10% level of confidence. A single star indicates a 5% level of confidence and a double star indicates a 1% level of confidence. Numbers in parentheses represent 1 standard deviation of the 9-member ensemble distribution of the number of tropical storms averaged over the 13-yr period

Basin	ATL	ENP	WNP	NIO	SIO	AUS	SPAC	TOTAL
VARI	6.5(*1*)	4(*0.4*)	12(*1.2*)	2.8(*0.4*)	5.3(*0.3*)	7.4(*0.8*)	2.3(*0.6*)	40.3(*1.5*)
CONST	6.6(*0.3*)	4.2(*0.5*)	11.5(*1.0*)	2.5(*0.4*)	4.8(*0.3*)	7(*0.8*)	2.1(*0.8*)	38.7(*1.2*)
CONST-VARI	+1.5%	+5%	−4.1%	−11%	**−9.4**%(*)	−5.4%	−8.6%	**−3.9**%

Table 2. Same as Table 1 but for the period 1989–2001

Basin	ATL	ENP	WNP	NIO	SIO	AUS	SPAC	TOTAL
VARI	6.4(*0.8*)	4(*0.8*)	10.9(*0.9*)	3.0(*0.3*)	6.08(*0.6*)	7.6(*0.6*)	3.3(*0.9*)	41.3(*1.8*)
CONST	6.3(*1.1*)	4.1(*0.2*)	11.3(*0.6*)	3.1(*0.3*)	6.15(*0.5*)	7.5(*0.5*)	3.6(*0.8*)	42(*1.9*)
CONST-VARI	−1.5%	+2.5%	+3.6%	+3.3%	+1.1%	−1.3%	+9%	+1.7%

Table 3. Ensemble mean number of tropical storm days per year over the period 1958–1970 simulated by the experiment VARI (variable GHG) and CONST(constant GHG of 1990). The last column represents the difference over all the basins. The last row represents the difference relative to VARI between CONST and VARI in percent. Bold numbers indicate when the difference is statistically significant according to the WMW test within a 10% level of confidence . A single star indicates a 5% level of confidence and a double star indicates a 1% level of confidence. Numbers in parentheses represent 1 standard deviation of the 9-member ensemble distribution of the number of tropical storm days averaged over the 13-yr period

Basin	ATL	ENP	WNP	NIO	SIO	AUS	SPAC	TOTAL
VARI	37(*5.4*)	38.2(*4.3*)	132(*8.5*)	32.5(*4.3*)	57(*4.3*)	83.8(*8.5*)	20.3(*4.3*)	400.8(*12*)
CONST	37.1(*2.7*)	39.9(*5.4*)	122(*11*)	28.8(*3.7*)	52(*4.5*)	79.3(*5.3*)	19.3 (*4.4*)	378.4(*12*)
CONST-VARI	+0.3%	+4.4%	**−7.6**%	**−11.3**%	**−8.8**%*	−5.3%	−4.9%	**−5.6**%**

statistic includes not only the frequency of storms but also its duration. CONST and VARI generate about 400 tropical storm days per year, which is significantly less than the observed number of tropical storm days (about 660 per year over the period 1958–2001). However the bias in the total number of tropical storm days is lower (in percentage) than the bias in the number of tropical storms. This is due to the fact that the model tropical storms in CONST and VARI tend to last longer (9 d on average) than observed tropical storms (7.3 d), which is also consistent with Camargo et al. (2005).

Table 3 displays the difference of number of tropical storm days between CONST and VARI over each ocean basin and globally for the period 1958–1970. Table 3 suggests that CONST displays less tropical storm activity than VARI globally and over all the basins except the North Atlantic and the eastern North Pacific, which is consistent with the difference of tropical storm numbers displayed in Table 1. The difference of tropical storm days between CONST and VARI is statistically significant within the 1% level of confidence globally (see ensemble distribution in Fig. 2), within the 5% level of confidence over the South Indian Ocean and is marginally significant (10% level of confidence) over the western North Pacific and the North Indian Ocean. Globally CONST produces 5.6% fewer tropical storm days than VARI. The difference is particularly strong over the North and South Indian Oceans. This suggests that the GHG concentration has a significant impact on the number of tropical storm days simulated by the coupled system.

Table 4 shows the difference of number of tropical storm days between CONST and VARI for the period 1989–2001. Globally CONST produced 3% more tropical storm days than VARI over that period. Over each ocean basin, except the Australian basin, the impact of an increase of GHG concentration on the frequency of tropical storms seems also consistent with the impact obtained during the 1958–1970 period (Table 3). Globally the difference between both experiments is statistically marginally significant within the 10% level of confidence (right panel of Figure 2). Over individual basins, the difference is statistically significant only over the North Indian Ocean within the 5% level of con-

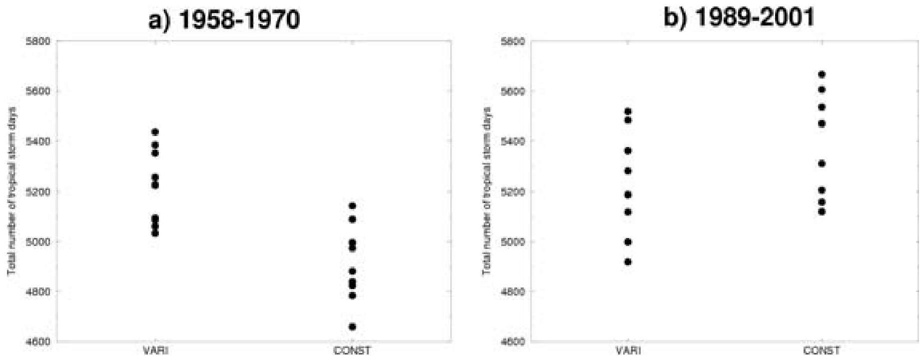

Fig. 2. Ensemble distribution of the global number of tropical storm days in CONST and in VARI for the period 1958–1970. Each black circle represents one ensemble member.

Table 4. Same as Table 3 but for the period 1989–2001

Basin	ATL	ENP	WNP	NIO	SIO	AUS	SPAC	TOTAL
VARI	36.7(*4.3*)	41.4(*3.4*)	112.4(*5.7*)	32.1 (*3.9*)	61.7(*5*)	88(*11*)	30(*5.8*)	402(*11*)
CONST	35.6(*6.4*)	41.3(*7.6*)	118.8(*10.6*)	36.6(*4.5*)	64.1(*3.8*)	84.8(*11*)	33(*3.6*)	414(*12*)
CONST-VARI	−3%	−0.2%	**+5.7**%	**+14**%*	+3.8	−3.6%	+10%	**+3**%

fidence and the western North Pacific within the 10% level of confidence.

The global map in Fig. 3 shows a grid point map of the difference of tropical storm days between VARI and CONST for both periods 1958–1970 and 1989–2001. The maps suggest that in the core areas where tropical storm activity takes place over the western North Pacific, the North Indian Ocean, the South Indian Ocean and the Australian basin, the increase of GHG concentration tends to reduce significantly the frequency of tropical storms. On the other hand, CONST seems to produce more tropical storm activity in regions in the North Pacific where there is usually not that much tropical cyclone activity during the period 1958–1970. This can probably be explained by the fact that CONST displays SSTs that are slightly warmer than in VARI by a few tenths of degrees. Tropical storms are observed only when SSTs are larger than a certain threshold of about 26°C (see Gray, 1979 for instance). Over the Atlantic, the difference between the frequency of tropical storms in CONST and VARI in Fig. 3 is much smaller than over the other ocean basins.

3.3. Intensity

The two experiments (CONST and VARI) do not display significant differences in the *intensity* of tropical storms. The probability distribution function of tropical storm maximum velocity obtained with CONST is almost identical to the distribution obtained with VARI (Fig. 4) during the period 1958–1970. This is also the case for the period 1989–2001 (not shown). The same result is obtained when using the minimum sea level pressure as a proxy of tropical storm activity rather than maximum velocity. This result seems to contradict Webster et al. (2005) and Emanuel (2005). However, although the numerical model has some skill in predicting the interannual variability of tropical storm *frequency* (Vitart, 2006), it does not display strong skill in predicting the interannual variability of tropical storm *intensity*. At such low resolution, very intense storms are quite rare in the model with very few of them having a maximum wind velocity exceeding $50\,\mathrm{m\,s^{-1}}$. Higher horizontal resolution would be needed to evaluate the impact of an increase of GHG concentration on the intensity of tropical storms.

4. Interdecadal variability of tropical storm frequency

According to the previous section, the GHG concentration seems to have a significant impact on the frequency of model tropical storms. However, it is not clear at this point if the impact is realistic or not. An advantage of the experiment setting is that the integrations span a period when observations are available, unlike more traditional doubling-CO_2 experiments.

In the present paper, we compare the interdecadal and interannual variability of tropical storms from 1958 to 2001 with observations. All the historical records of observed tropical cyclones have been obtained from Neumann et al. (1993), http://weather.unisys.com/hurricane/index.html and the Joint Typhoon Warning Center Products website (http://199.10.200.33/jtwc.html). In this section, results over the North Indian Ocean are not discussed, since the historical data over this basin displays a strong inconsistency in the number of Indian tropical cyclones before and after 1976. For the Atlantic, eastern North Pacific and western North Pacific only the forecasts starting on 1st May are considered, and over the Southern

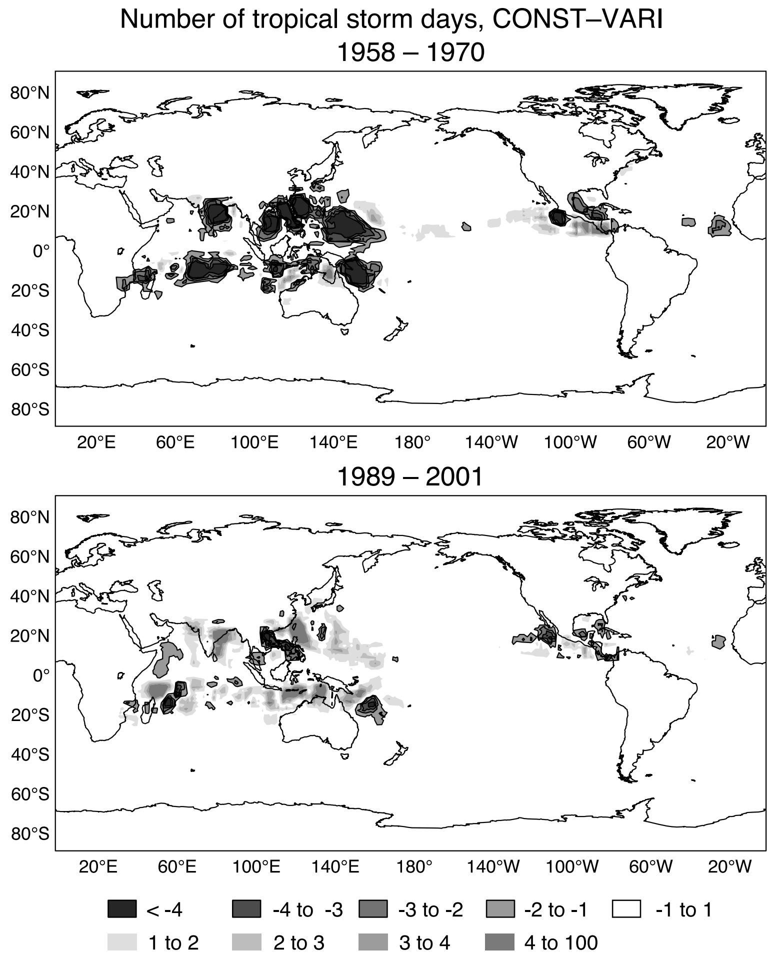

Fig. 3. Global map of the difference of tropical storm days between VARI and CONST. The number of tropical storms within 10 degrees has been calculated over each grid point and averaged over the period 1958–1970 and over the 9 members of the ensemble.

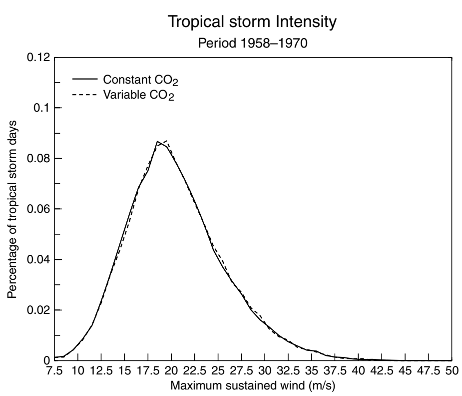

Fig. 4. Probability distribution function of the maximum wind velocity of all the tropical storms in CONST (slid line) and VARI (dotted line) from 1958 to 1970.

Hemisphere, only the forecasts starting on 1st November are taken into account. The first month of the forecast discarded, in order to remove the most deterministic part of the forecast.

Table 5. Linear correlation between the 10-year running mean of observed tropical storm frequency with the 10-yr running mean of tropical storm frequency in CONST and in VARI from 1963 to 1996

Basin	ATL	ENP	WNP	SIO	AUS	SPAC
VARI	0.3	0.7	0.1	0.3	0.2	0.80
CONST	0.2	−0.1	−0.2	−0.2	0.0	0.70

A 10-yr running mean has been applied to the time series of the number of tropical storms predicted in each experiment (VARI and CONST) and in observations in order to filter the interannual signal. The linear correlations (Table 5) seem to be higher in VARI than in CONST in all the basins, although the improvement is not very large, probably because the natural interdecadal variability of tropical storms plays a more important role during this period of time than the impact of GHG concentration. However, over some basins, like the South Indian Ocean, the interdecadal variability seems to be more realistic with variable GHG concentration than with constant GHG concentration (Fig. 5).

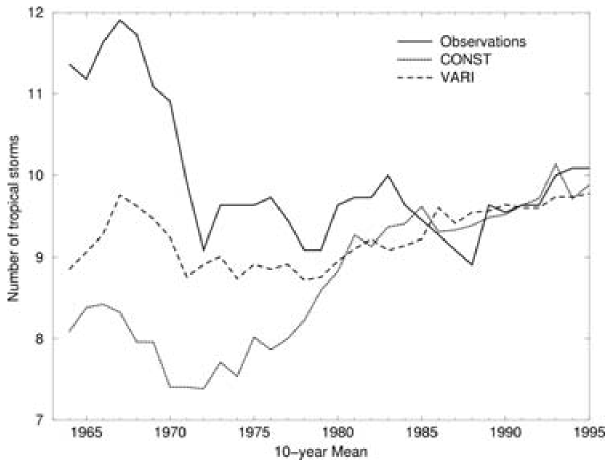

Fig. 5. 10-yr running mean of the number of tropical storms over the South Indian Ocean from 1963 to 1996. The solid line represents observations, the dotted line represents CONST and the dashed line represents VARI. The number of model tropical storms has been multiplied by a factor so that the average number of model tropical storms during the period 1981–2001 matches the observed climatology.

A linear trend analysis has been performed on the 10-yr running mean of VARI, CONST and observations, and the trend obtained over each ocean basin is displayed on Fig. 6. The GHG concentration seems to have an impact on the trend of model tropical storms over all the basins except the Australian basin.Over 4 of the basins: the Atlantic, the eastern North Pacific,the Australian basin and the South Pacific, VARI displays a trend closer to observations than CONST. Over the Atlantic the trend in VARI is close to the observed trend, whereas CONST displays a trend of opposite sign. However, this may be due just to chance, since the difference between CONST and VARI was not statistically significant in Tables 1 and 2. The western North Pacific is the only basin where using varying GHG concentrations produces a trend that is worse than when using constant GHG concentration. Although, there is some uncertainty in the quality of the observed data (it is not always clear how real the observed trends displayed in Fig. 6 are), Fig. 6 suggests that the use of varying GHG concentration helps to produce in general a more realistic trend in the frequency of tropical storms.

After removing the trends (Table 6), the South Indian Ocean displays a significantly higher linear correlation with observations for both VARI and CONST than before removing the trend (Table 5). This was because both VARI and CONST have a trend of opposite sign to the observe trend over this basin. Over the other ocean basins, the correlation are quite low, suggesting that the high correlation over the eastern North Pacific and the South Pacific in Table 5 were due to the fact that the model has a trend consistent with observations rather than a skill in simulating the interdecadal variability around this trend. Overall the correlations obtained with CONST and VARI are much closer to each other after removing the trend than before. The interdecadal variability of the number of tropical storms in CONST and VARI are indeed more correlated after removing the trend than before over most of the basins. This suggests that the increase of GHG concentration impacts primarily the trend of the tropical storm frequency, but it does not seem to have a significant impact on the interdecadal variability around this trend, except maybe over the South Indian Ocean.

Those results show that the GHG concentration has a small positive impact on the interdecadal variability of model tropical storms, mostly through the trend, and that the inclusion of greenhouse gas updated annually improves generally the seasonal forecasts of tropical storms, as it does with other predicted variables (Doblas-Reyes et al., 2006).

5. Large-scale circulation

The reason why the model seems to produce less tropical storms with increased GHG concentration is investigated by evaluating the impact of the increase of GHG concentration on thermodynamic and dynamic variables that affect the frequency of tropical storms.

The surface temperature predicted by the coupled integrations for the period has been averaged over all the starting dates from 1958 to 1970 (Fig. 7) for lead times varying from 1 to 6 months. A weakness of the experimental setting is that the experiment with constant GHG starts with initial conditions from ERA40, where variations of GHG concentration are taken into account. Therefore the coupled experiment in CONST which has GHG concentration of the 1990s does not start in equilibrium with its initial conditions. However according to Fig. 7, the model seems to reach an equilibrium after about 4 months of integrations, when the difference of global surface temperature stabilises around 0.12 degrees. Since the tropical storms are tracked over the period month 2 to 6, Fig. 6 suggests that the results presented in the previous section are probably an underestimation of the impact of the increase of GHG concentration during the second half of the 20th century. However, since the difference in global surface temperature reaches an equilibrium by month 4 and most of the tropical cyclone activity occurs in months 4, 5 and 6 (starting date of May for the Northern Hemisphere), the underestimation of the impact of GHG concentration on tropical cyclone frequency should be small. Inspection of the difference of global temperature for the period 1989–2001 between CONST and VARI (not shown) leads to the same conclusion, although the difference is twice as small for the period 1958–1970, and the sign is opposite (VARI produces warmer global temperature than CONST during the period 1989–2001).

The difference of global temperature between VARI and CONST for the period 1958–1970 averaged over the last 5 months of the forecast indicates some strong geographical variations (Fig. 8). Over land, the difference between CONST and VARI can exceed 0.4°C. Over sea the difference tends to be much lower, generally below 0.1°C in the tropical regions.

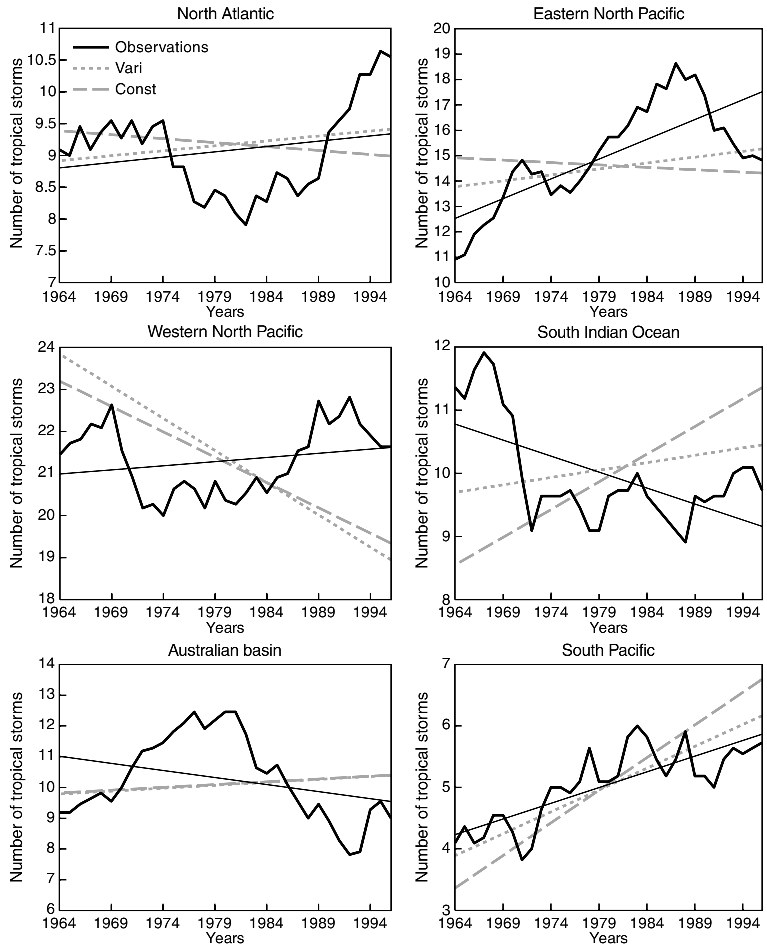

Fig. 6. 10-yr running mean of the number of observed tropical storms (solid curve) over the Atlantic, the eastern North Pacific, the western North Pacific, the South Indian Ocean, the Australian basin and the South Pacific from 1963 to 1996. The solid line represents the estimated trend in observations, the dotted line represents the estimated trend in VARI and the dashed line represents the estimated trend in VARI.

Table 6. Same as Table 5 but after removing the estimated trend

Basin	ATL	ENP	WNP	SIO	AUS	SPAC
VARI	0.2	0.4	0.2	0.8	0.3	0.2
CONST	0.3	0.1	0.3	0.6	0.2	0.1

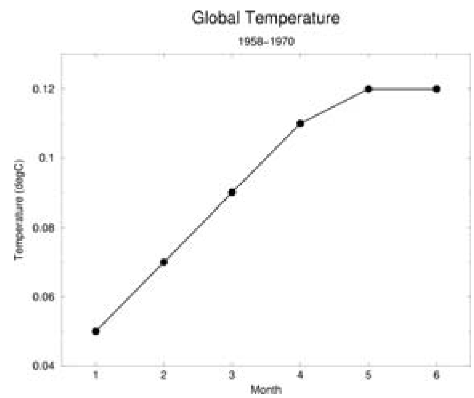

Fig. 7. Difference of global surface temperature averaged over the period 1958–1970 and all the ensemble members between CONST and VARI as a function of the lead time (in months).

The warming of SSTs due to the increase of GHG concentration should be conducive to more tropical cyclone activity. However, the impact of the increase of GHG concentration at other levels of the troposphere can also have an important impact on the frequency of tropical storms. Figure 9 displays a vertical cross section of the difference of temperature (left panel) and mixing ratio (right panel) between CONST and VARI. The vertical profile has been computed over the main tropical storm development region in the Southern Hemisphere (30E–160W, 0–20S), all the ensemble members and the five last months of all the forecasts starting on 1st November 1958–1970. The Southern Hemisphere was chosen because it is the region where CONST and VARI display the largest difference in tropical storm frequency. According to Fig. 9, the increase of GHG concentration creates a warmer and moister troposphere. The warming is higher in the top layers of the troposphere than at the surface. In order to evaluate how this difference in vertical profile could affect tropical cyclone activity, the Convective Available Potential Energy (CAPE) has been computed with CONST and VARI over the same region as in Fig. 9. Results (Fig. 10, left panel) suggest that the CAPE is

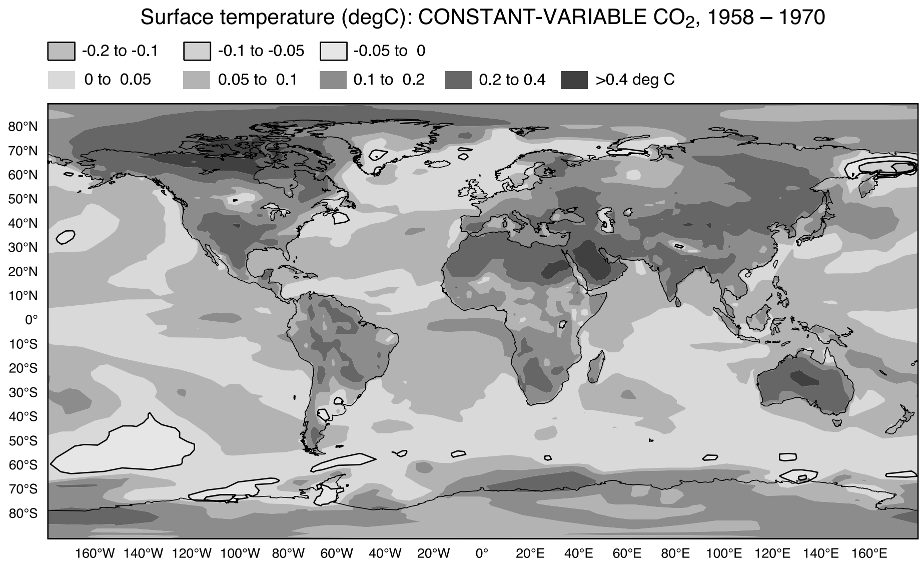

Fig. 8. Map of the difference of global surface temperature averaged over the period 1958–1970, over all the ensemble members and over the last 5 months of the forecasts between CONST and VARI.

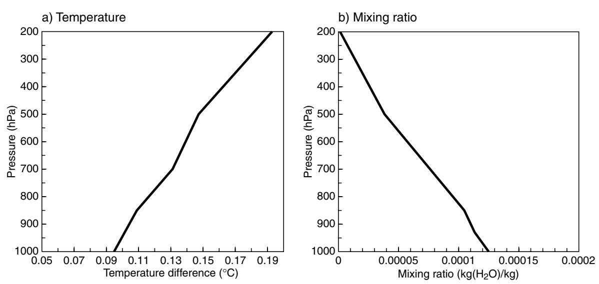

Fig. 9. Vertical profile of the difference of (a) temperature (in deg C) and (b) mixing ratio (kg/kg) between CONST and VARI (CONST-VARI). The vertical profiles have been averaged over the tropical storm main development area in the Southern Hemisphere(30E–160W, 0–20S), over all the ensemble members and over all the forecasts starting on 1st November 1958 to 1970 and the last five months of the forecast.

slightly higher in CONST than in VARI for the period 1958–1970. An alternative CAPE measure, called CAPE90 (Knutson and Tuleya, 1999), assumes an environmental relative humidity of 90% for the air parcel lifted from the lowest level. This is motivated by the fact that a parcel with an initial relative humidity of 90% is more representative of what would occur in the eye-wall region (Holland, 1997; Shen et al., 2000). Vitart et al. (2001) investigated the impact of different convective parameterizations on the frequency of model tropical storms. They found that the difference of CAPE90 between two different models was more consistent with the difference of tropical storm activity than the difference of CAPE, suggesting that CAPE90 may be a better indicator of model tropical storm activity than CAPE. According to Fig. 10 (middle panel), the ensemble distribution of CAPE90 is higher in VARI than in CONST. The difference is statistically significant within the 5% level of confidence according to the WMW-test. This would suggest that the thermodynamic conditions in VARI may be conducive to more tropical storm activity, and could explain why VARI has more tropical storm activity in the Southern Hemisphere than CONST. The same results were obtained over the western North Pacific with the forecasts starting in May. For the period 1989–2001, CONST displays *higher* CAPE90 than VARI, which supports the conclusion that an increase of GHG concentration creates less favorable conditions for tropical cyclone activity in this model.

Dynamical variables that have an impact on tropical storm frequency include vertical wind shear and low level vorticity (see Gray 1979 for instance). The vertical wind shear tends to be higher (lower) over the Pacific and Indian Oceans in CONST than in VARI during the period 1958–1970 (1989–2001). The right panel of Fig. 9 displays the ensemble distribution of vertical wind shear averaged over the region where most tropical cyclones develop in the Southern Hemisphere (30E–160W, 0–20S). Over this region, the vertical wind shear in VARI is statistically significantly lower than in CONST during the period 1958–1970, which would be conducive to more tropical cyclone activity, in agreement with the results presented in the previous section. VARI also displays higher 850 hPa vorticity than CONST over most of the tropical Pacific and Indian Ocean (not shown). Those results suggest that the increase of GHG concentration has a statistically significant impact on dynamical variables, which could also explain the decrease of model tropical storms when the GHG concentration increases.

In summary, the changes in CAPE90 and in the dynamical parameters would favor *a decrease* in the frequency of model tropical storms with increased GHG concentration. It is not clear which factor is more important.

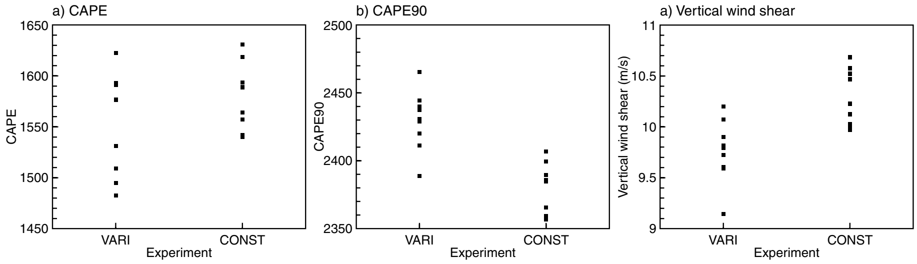

Fig. 10. Ensemble distributions of (a) CAPE, (b) CAPE90 and (c) vertical wind shear between 200 and 850 hPa. The fields have been averaged over tropical storm main development area in the Southern Hemisphere (30E–160W, 0–20S) over all the forecasts starting on 1st November 1958 to 1970 and the last five months of the forecast. Each black square represents one ensemble member.

6. Conclusion

The present paper discussed the impact of applying a variable GHG concentration on the frequency of model tropical storms in a seasonal forecast context, instead of keeping the GHG concentration constant. This experiment is different from previous experiments about the impact of GHG concentration on tropical storm frequency: it uses ensembles of 6-months coupled ocean-atmosphere seasonal integrations. This experiment is likely to underestimate the impact of the increase of GHG concentration since the 1950s, since the experiment with constant GHG starts with initial conditions that are not in equilibrium with the model physics.

A main conclusion of this paper is that the increase in GHG concentration since 1958 seems to have been conducive to reduced tropical cyclone activity over most of the ocean basins. This result is consistent with Bengtsson et al. (1996), Sugi et al. (2002) and Oouchi et al. (2006) who found a decrease in tropical cyclone activity when doubling GHG concentration. Bengtsson et al. (1996) also found that the reduction of tropical cyclone activity was more pronounced in the Southern Hemisphere. It is also intriguing that Webster et al. (2005) found that the number of tropical cyclones and tropical cyclone days has decreased in all basins except the North Atlantic during the past decade. This pattern is consistent with the impact of GHG in the present study, although the present study did not find a reduction of tropical storm days over the eastern North Pacific when the GHG concentration increases.

A second conclusion is that the interdecadal variability of tropical storms seems to be slightly improved in VARI compared to CONST. This suggests that it is important for seasonal forecasting systems to take account of the variability of GHG concentration (Doblas-Reyes et al., 2006). This is not an obvious conclusion, since it is often assumed that a 6-month integration is too short for an increase or decrease of GHG concentration to have any impact. For example, none of the 7 models which took part in the DEMETER project had variable GHG. This illustrates that seasonal forecasting systems being calibrated over longer hindcast periods start to share the same issues as other climate models.

Finally, the decrease of tropical storm frequency due to the increase of GHG concentration could be linked to a decrease of CAPE90 due to a warmer upper troposphere or to feedbacks on vertical wind shear or low level vorticity. Bengtsson et al. (1996) also noticed that the doubling of CO_2 concentration created large-scale conditions (vertical wind shear, low-level vorticity) less conducive to tropical cyclone activity. The results presented in this paper are also very consistent with Sugi et al. (2002) who also found, using an atmosphere-only GCM forced by prescribed SSTs, that an increase of greenhouse gas was conducive to an overall more stable atmosphere, because of a larger increase of temperatures in higher altitudes.

In the present set of experiments, the aerosol concentration was set to a fixed value. Future experiments will investigate the impact of varying aerosol concentration on the interdecadal variability of model tropical storms.

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