4.6 ASSESSMENT OF CHANGES IN WINTER EXTRATROPICAL CYCLONES WITH INCREASING CO_2

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1. INTRODUCTION

As part of the general concern about the nature of climate change in a warmer world much attention is being paid to what changes extratropical cyclones would experience with further warming caused by increasing CO_2 in research community. A number of studies using general circulation models (GCMs) seem to be in agreement in predicting a general reduction of cyclone frequency (Zhang and Wang 1997, Carnell and Senior 1998, Sinclair and Watterson 1999, Geng and Sugi 2003). Also they have showed that there is a decrease of the lower-troposphere baroclinicity but an increase in upper tropospheric baroclinicity as the globe warms up due to increasing CO_2 (Hall et al. 1994, Zhang and Wang 1997, Carnell and Senior 1998, Knippertz et al. 2000).

Despite these agreements, there are still discrepancies in detail about how these different changes of different level baroclinicity affect surface cyclone frequency and features. Zhang and Wang (1997), Carnell and Senior (1998) and Sinclair and Watterson (1999) concluded that cyclones are likely to decrease in their numbers due to the reduction of the low troposphere baroclinicity. On the other hand, Schubert et al. (1998) showed that there is an increase of eddy activity at 500 hPa geopotentisl height over the North Atlantic and Western Europe because of an increase of the mid-troposphere baroclinicity. Furthermore, Lunkeit et al. (1998) suggested that storm track activity is influenced by both lower and upper troposphere baroclinicity but one influence can dominate in a specific region and they attempted to explain the increase of cyclone activity over western Europe in terms of the increase of the upper troposphere baroclinicity.

In this paper we explore these issues by documenting changes in cyclone behavior in the recent observed record, and in a climate model simulation undertaken with enhanced levels of greenhouse forcing. We make use of an automatic cyclone location scheme to identify cyclones at a number of levels in the vertical. We are particularly interested in the trends at the various levels, and to what extent the vertical 'organisation' of cyclones changes.

In this paper, the climatology of winter cyclone features and their vertical structure is presented first, and then the results from CSIRO Mark2 atmosphere-ocean coupled general circulation model (AOGCM) are compared to this.

2. DATA AND METHODOLOGY

The observational data set we use here is the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) reanalysis-II data set (hereafter, NCEP2) (Kanamitsu et al. 2000, 2002). The data include 6 hourly global analyses of mean sea level pressure (mslp), and 925, 850, 700, 600 and 500 hPa geopotential heights (hereafter, *Zheight*). This data set covers the period of 1979-2000.

Results with an increasing CO_2 scenario are obtained from the CSIRO Mark2 AOGCM. This model comprises the atmosphere, ocean, sea ice and land biosphere sub-models (Wu et al. 1999). The atmospheric model is spectral with R21 wave truncation and 9 sigma vertical levels. The ocean model is the standard GFDL (Geophysical Fluid Dynamics Laboratory) model but includes oceanic

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eddy-induced advection (Hirst and McDougall 1996), according to the Gent and McWilliams' scheme (Hirst 1999). The sea ice model (Gordon and O'Farrell 1997, O'Farrell 1998) includes the three-layer thermodynamic treatment of Semtner (1976), with ice dynamics based on Flato and Hibler (1992).

The CO_2 forcing in the control run is set at the pre-industrial level of CO_2 of 330 ppmv equivalent CO_2. In the 'transient' run, the equivalent CO_2 observed for the calendar years 1880-1990 is used, and then CO_2 increases according to the IS92a scenario for 1991-2082 (IPCC 1995). The equivalent CO_2 reaches three times the 1880 value at 2082 and is held constant thereafter (Hirst 1999).

For this research six level mslp and geopotential height data from the control run like from NCEP2 and four levels (mslp, Z850, Z700 and Z500) of data from the transient run are available. In what follows we compare 22 year averages in NCEP2 and in the model simulations.

In order to detect cyclones at each level, the Melbourne University cyclone finding and tracking scheme (Simmonds and Keay 2000a, Keable et al. 2002) is used.

The vertical organization over surface cyclones is determined in a series of steps : First, we find the location and time of maximum depth of a surface cyclone. In a circle of 4^o latitude radius centered on the location and the time found, we search for the vertical extension of the cyclone at the next data level. This tracking is continued to Z500.

3. RESULTS

3.1 Climatology over the last 22 years

a. Cyclone properties

Table 1 summarizes the features of winter cyclones (December-January-February (DJF) 1980-2000 in the Northern Hemisphere (NH) and June-July-August (JJA) 1979-2000 in the Southern Hemisphere (SH)). Cyclones were found and tracked separately with the cyclone scheme at six levels. In comparison of cyclone properties at six levels, mslp cyclones seem to have smaller scale but greater intensity than higher level cyclones in both hemispheres. An interesting fact found in this table is that the mean cyclone system density and intensity show decreases from the surface to

		SD	R	I	D
NH	Z500	1.74	7.14	8.97	82.56
	Z600	1.45	7.36	7.08	73.88
	Z700	1.22	7.39	6.20	67.16
	Z850	1.05	7.13	6.08	62.28
	Z925	1.04	6.94	6.25	61.82
	msl	1.57	5.33	7.80*	49.30*
SH	Z500	1.49	7.73	7.78	83.47
	Z600	1.32	7.81	6.45	74.29
	Z700	1.15	7.70	5.97	68.05
	Z850	1.11	7.26	6.41	64.70
	Z925	1.18	7.04	6.82	64.83
	msl	1.80	5.53	8.48*	50.92*

Table 1: Mean winter cyclone properties in 1979-2000. SD: system density (the mean number found in a 10^3 (^{o}lat$)^2$), R: radius (^{o}lat), I: intensity-$\nabla^2 P$ (m/(^{o}lat$)^2$), D: depth (m). * designates the converted values from hPa to geopotential height by the Hydrostatic equation.

Z700, but then start to increase again as the height increases. It is likely to reflect the influence of freedom from topography and boundary conditions, more wave-like patterns in the higher atmosphere and the presence of the jet stream in the upper troposphere.

In the NH there are more cyclones and greater cyclone intensity above Z850 compared to the SH while the opposite is found from Z850 to the surface. It might be due to the influence of greater jet stream and a role of continentality and topography in the NH by inducing quasi stationary waves and making regions of the NH very conducive to cyclone development. On the other hand, the SH provides more areas for the lower tropospheric maritime cyclones to develop. Also, SH winter cyclones are larger than NH counterparts at all levels. This result is consistent with that of Simmonds (2000). Simmonds (2000) suggested that in the the SH which is more zonally symmetric cyclones would have more freedom to grow to larger size than in the NH where stationary long waves often make cyclones crowd together. Consequently, SH cyclones appear to be deeper than the NH counterparts with no respect to the vertical levels.

The derived trends in cyclone properties at msl, Z850 and Z500 are displayed in Table 2. NH cyclone system density does not show any significant trend in winter at the three levels although

		NH		SH	
Z500	SD	0.1		2.3	(95%)
	R	-3.2		1.9	
	I	-11.4		19.5	(99%)
	D	-142.5		259.0	(99%)
Z850	SD	-0.6		1.6	
	R	-1.8		0.1	
	I	6.8		23.6	(99%)
	D	16.3		272.7	(99%)
msl	SD	-0.6		-4.7	(95%)
	R	-1.0		6.0	(99%)
	I	1.2	(90%)	2.0	(99%)
	D	4.2		29.8	(99%)

Table 2: Slopes of cyclone property variations in 1979-2000 in the SH and 1980-2000 in the NH. The numbers should be multiplied by 10^{-3}.

slight decreases are seen at the surface and Z850 but an increase at Z500. At the surface and Z850 cyclone intensity has increased but Z500 cyclone intensity has decreased. Among these, only mslp cyclone intensity increase is significant only at 90% confidence level (hereafter c.l.). Cyclone scale shows decreases at all levels. Lastly, NH cyclones seem to get slightly deeper at the surface and Z850 , but cyclone depth has decreased at Z500 over the last two decades. However, these changes of cyclone scale and depth are not significant. By contrast, SH cyclone system density has decreased (95% confidence level) at msl but increased at Z850 and Z500 (95% c.l.) over the 22 years. Cyclone intensity is found to have significantly increased during this period at all levels on 99% c.l. Furthermore, cyclone scale shows increases. Consequently cyclones have been deeper from the surface to the mid-troposphere on 99% c.l. in the SH.

b. Vertical organization of cyclones

We find from our "vertical tracking" that about 41% and 36% of surface extratropical cyclones have well organized vertical structure which can be traced all the way to Z500 in winter in the NH and SH, respectively. Furthermore, this percentage has increased over our 22 years of record (Figure 1), but only the trend in the SH is significantly different from 99% c.l. The enhancement of vertical organization of cyclones might be strongly related to the increase of mean depth of SH extratropical cyclones in the SH (Simmonds and Keay 2000b

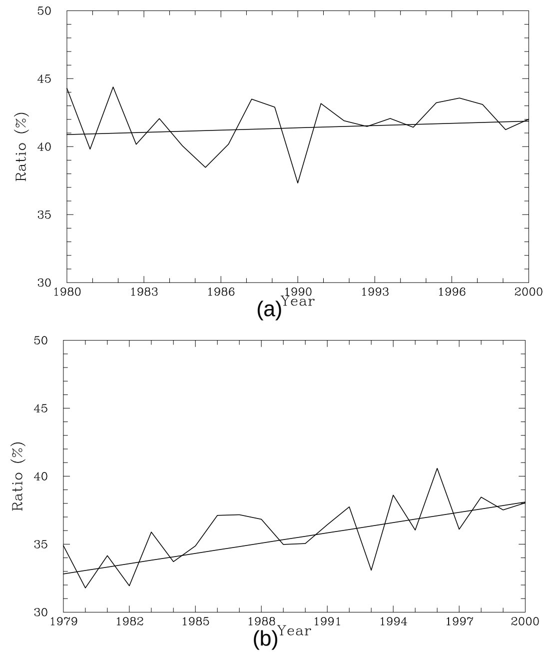

Figure 1: Time series of the ratio of the number of well-organized cyclones to the entire mslp extratropical cyclones in winter seasons in 1979-2000. (a) NH and (b) SH

and Table 2).

The surface cyclone features show clear differences according to whether or not surface cyclones are vertically well organized. We compare the surface cyclone properties when the surface cyclones have vertically well organized structure connecting to Z500 and the counterparts when the vertical organization is ended at Z700. Table 3 suggests that the surface cyclones having a Z500 cyclone partner are more intense, larger and deeper than those ending their connection at Z700 or lower. Moreover, the mslp-Z500 coupled cyclones appear to have twice the lifespan of the others.

When surface cyclones experience their deepest stages, the average distance between Z500 and mslp cyclone centers is about 388 km and 384 km in winter in the NH and in the SH, respectively. In fact, the winter cyclone distance is the furthest compared to other seasons, strongly indicating that stronger baroclinicity drives cyclones in winter. This distance has reduced for the last two decades, and these decreases are -1.74 and -1.96 km per annum (99% c.l.) in the NH and SH (Figure 2). It might

	NH		SH	
	M-5	M-7	M-5	M-7
SD	0.44	0.30	0.45	0.38
R	5.55	4.98	5.76	5.12
I	0.96	0.68	1.00	0.75
D	6.22	3.97	6.34	4.18
Lifespan (days)	4.00	2.00	4.50	2.25

Table 3: Comparison of the cyclone properties when the mslp cyclones have well organized structure up to Z500 (M-5) and the counterparts when there is no further connection above Z700 (M-7).

imply that cyclones have become more barotropic at the full development stage over the last 22 years.

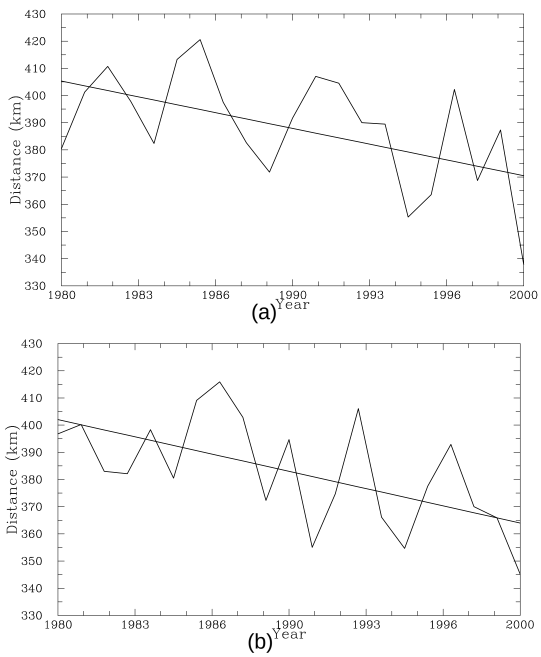

Figure 2: Time series of the average distance between coupled Z500 and mslp cyclone centers. (a) NH and (b) SH

Figure 3 presents a summary of the positions of Z500 cyclones relative to their surface counterparts and the number of couples in each direction (all directions are divided by 45^o sectors). The couples of the surface cyclone and Z500 cyclone are counted in each 10^o latitude longitude box and distributed according to the relative direction of the Z500 cyclone to the surface one. The arrows point in 8 directions of the compass and their length represents the number of pairs more than 20 in each direction. Most of the Z500 cyclones coupled with surface cyclones are positioned westward of the surface feature. The relative positions of Z500 cyclones to the surface counterparts seem to distribute evenly at all western directions (they are not seen in Figure 3 due to their small number of pairs). Nevertheless, the most common coupling is found in 45^o North or South from the location of surface cyclones in the NH. Furthermore, vertical organisation occurs more actively in the Pacific than in the Atlantic Ocean in general, and in the Atlantic the east coast of Canada and Greenland is favored for this. Also, it is noticeable that the cyclones occurring at the Great Lakes and the Hudson Bay tend to have a well organized vertical structure. On the other hand, Arctic cyclones seem not necessarily to have Z500 cyclone partners in their deepest stages. In the SH, it is shown that a number of cyclones occurring along the coast of East Antarctica have a strong component of

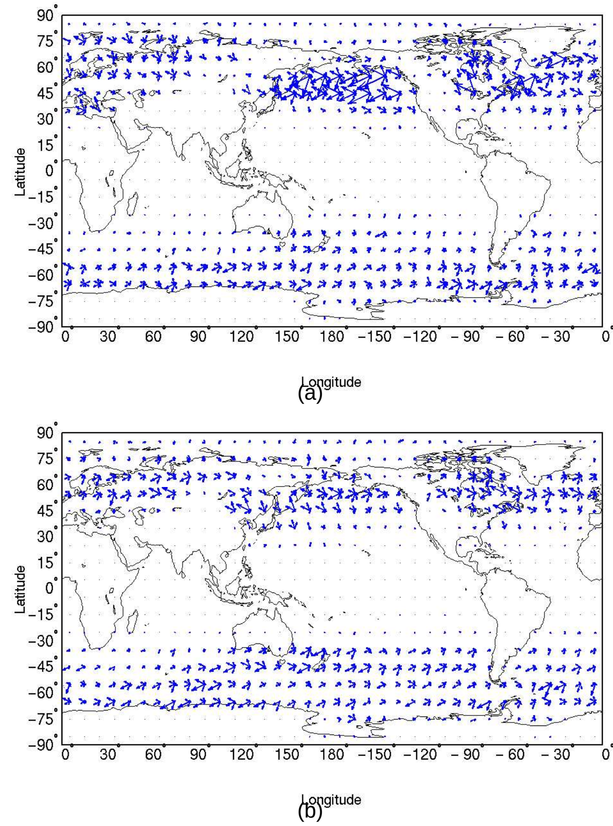

Figure 3: Relative positions of Z500 cyclones to their partners at mean sea level (the length of arrows is proportional to every 20 couple increase from 20 pairs). (a) NH and (b) SH

southward tilt, which is different from the cyclones at the coast of West Antarctica. Also, it appears that there are more preferred directions for Z500 cyclones to interact with their surface counterparts over the Southern Ocean south of Australia and New Zealand and the southeastern Pacific Ocean.

Moreover, we present the times at which Z500 cyclones are associated with the surface cyclone deepest stages. As expected from above results, a number of Z500 cyclones have their maximum development at the same time as the surface cyclones (Figure 4). This case occupies about 11% of the cyclones having Z500 partners. Also, it is interesting to note that the deepest stages of Z500 cyclones do not show any particular preference to pre- or post-stage of those of surface counterparts although slightly more percentage is found in the case that Z500 cyclones experience the deepest stages after the surface ones do.

Lastly, we document these properties of vertical structure of explosive cyclones which Lim and Simmonds (2002) studied and showed that there have been increases of them over the last two decades. About 64% and 61% explosive cyclones are found to have vertically well organized structure reaching to Z500, and about 15% of mslp and Z500 cyclones appear to gain their maximum depths at the same time.

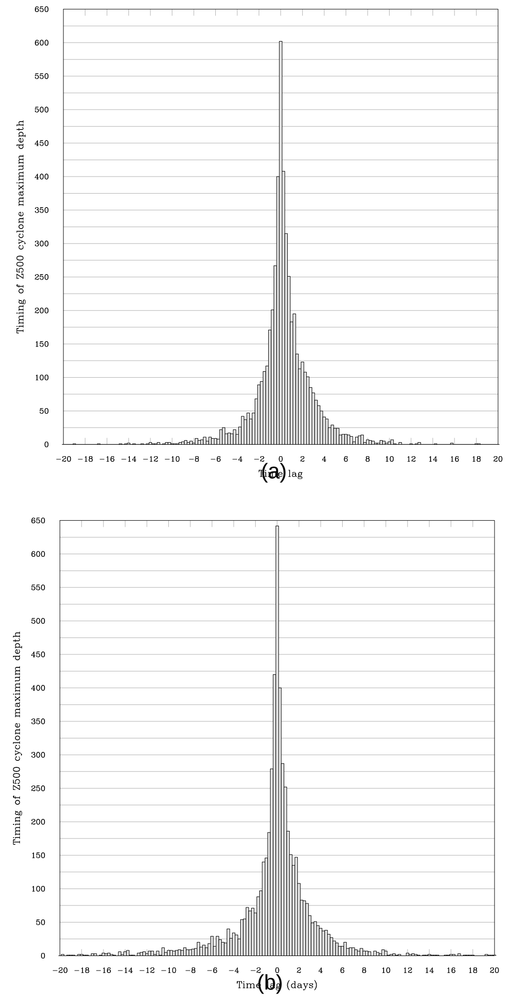

Figure 4: Relative positions of Z500 cyclones to their partners at mean sea level (the length of arrows is proportional to every 20 couple increase from 20 pairs). (a) NH and (b) SH

3.2 Simulated changes of cyclone characteristics with increasing CO_2

a. Cyclone properties

Since a technical problem has been found over Antarctica likely in the process of recalculation of mslp, detection of cyclones over and around Antarctica are somewhat inaccurate with the data from CSIRO Mark2 model. Consequently, fewer cyclones are found at msl than Z925, a result different from that obtained with the observations (Table 1). In the case of calculating cyclone system density in 25^o and 65^oS excluding Antarctic region, we obtain more cyclones at the surface than at Z925 as we do with NCEP2 data (not shown). Having taken this structure into account, we examine the behavior of cyclones simulated in the control run. The results of 22 year averages of cyclone properties from the CSIRO model control run give a reasonable agreement with those from NCEP2 although more numbers, smaller scale, and less depth of cyclones are simulated in our model at all vertical levels except for the surface, and cyclone intensity is slightly underestimated at all levels (Table 4). The simulated results capture the decreases of cyclone properties from the surface to Z850 or Z700 and the increases above those levels as found in NCEP2 results. Moreover, NH Z500 cyclones are more in number and stronger in intensity than those in the SH Z500 in the CSIRO model like in NCEP2. Therefore, in this paper it would not be a significant problem not only because the CSIRO model cyclones represents the observed cyclones reasonably well, but also because the erroneous feature is included in all model runs, and we will focus on the differences between the control and transient runs.

NH				
		CONT	$2xCO_2$	$3xCO_2$
Z500	SD	1.81	1.75	1.74
	R	6.91	6.92	6.88
	I	7.63	7.27	6.92
	D	73.33	70.61	66.90
Z700	SD	1.22	1.18	1.16
	R	7.04	7.05	7.06
	I	5.22	5.13	5.01
	D	60.17	59.53	58.09
Z850	SD	1.15	1.12	1.10
	R	6.71	6.76	6.82
	I	5.48	5.48	5.42
	D	56.07	56.79	56.67
MSL	SD	1.14	1.16	1.12
	R	6.73	6.81	6.91
	I*	6.8	6.63	6.55
	D*	68.51	68.51	68.17
SH				
Z500	SD	1.73	1.66	1.62
	R	7.27	7.29	7.29
	I	7.54	7.64	7.48
	D	75.12	76.93	76.17
Z700	SD	1.46	1.41	1.37
	R	7.45	7.48	7.49
	I	5.79	5.92	5.89
	D	64.23	66.18	66.39
Z850	SD	1.43	1.36	1.35
	R	7.19	7.23	7.24
	I	6.15	6.25	6.22
	D	63.78	65.35	65.31
MSL	SD	1.44	1.37	1.31
	R	7.01	7.07	7.11
	I*	6.8	6.8	6.63
	D*	68.60	69.53	68.85

Table 4: Comparison of cyclone properties from CSIRO Mark2 AOGCM control run and transient run in 25-90^o latitudes. * denotes the parameters whose values are converted to m from hPa.

Having been satisfied with the quality of CSIRO Mark2 model to represent the present climate, now let us move to the responses of cyclone features to increasing CO_2. Since only four vertical levels are available in the transient run - mslp, z850, z700 and z500, the results are presented focused on the four levels available in all data sets although we use six vertical levels of the control run data to check the sensitivity of our model.

In both hemispheres cyclone frequency decreases as the CO_2 increases at all levels except for the NH surface. In terms of scale, cyclones seem to have larger radii in the warmer world. NH cyclone intensity is likely to decrease with increasing CO_2. By contrast, SH cyclone intensity increases between the control CO_2 and $2xCO_2$ 22-year averages. However, the intensity decreases from $2xCO_2$ to $3xCO_2$. These comments apply at all levels. NH cyclones tend to get less depth, and the degree of the reduction is greater at Z500 than the surface. On the other hand, SH cyclone depth seems to increase as the CO_2 is doubled, but then there is a slight decrease up to tripled CO_2. Nevertheless, the increase and decrease of these parameters tend to depend on each region of the consideration (not shown).

b. Vertical organisation

About 43% and 50% of the control model cyclones have vertically well organized structure up to Z500 in the NH and SH, respectively (Table 5). With increasing CO_2, the ratio of cyclones having well organized vertical structure increases. Interestingly, the mslp and Z500 cyclone separation decreases as CO_2 increases in both hemispheres. This is consistent with the results we have from NCEP2. In addition, it is noticeable that there are more mslp-Z500 couples experiencing the deepest stage at the same time in the NH with increasing CO_2.

In addition, the mean values from vertically well organized cyclones and shallow structured ones are nearly identical in NCEP2, CSIRO control run and transient run. In terms of directions of the tilts between mslp and Z500, our model simulates the percentages of each direction well enough, and it appears that there is no particular change with a CO_2 concentration change.

		CONT	$2xCO_2$	$3xCO_2$
Ratio	NH	42.6	43.3	45.1
(%)	SH	49.8	50.8	51.6
Distance	NH	505.7	494.1	485.8
(km)	SH	450.0	441.7	428.5
Concurrent	NH	8.9	9.2	9.9
deepening (%)	SH	9.1	9.1	9.0

Table 5: Changes of vertically well structured cyclones according to CO_2 concentration in the control run (CONT) and transient runs ($2xCO_2$, $3xCO_2$).

4. Concluding remarks

In this paper we analyze the changes of winter extratropical cyclones in terms of the characteristics such as frequency, intensity, depth, scale and vertical structure simulated in the 22 year period of NCEP2 and in the 300 years of CSIRO Mark2 AOGCM with increasing CO_2.

Overall, it appears in NCEP2 that SH cyclones have experienced more significant changes in some of their properties and in the vertical structure than their NH counterparts. Also, with increasing CO_2 the tendencies of the changes of cyclone properties are likely consistent through the lower and mid troposphere in terms of averages over each hemisphere although different changes of baroclinicity are expected at the lower and mid troposphere. However, detailed regional analyses should be followed in the future. Lastly, the results of vertical organization of cyclones in the CSIRO simulations are in good agreements with those in NCEP2. Therefore, some of present changes in cyclone vertical structure seem to be following the patterns possibly cyclones experience in the warmer world.

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