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Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
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1. Introduction

Within the ENSEMBLES project, RT4 is the Research Theme devoted to advancing our understanding of the basic science issues. This aim is pursued through the elucidation of the key processes that govern climate variability and change, and that determine the predictability of climate on timescales of seasons, decades and beyond.

Numerical models, in particular general circulation models (GCMs), are one of the powerful tools for the investigation of the physical processes governing the Earth's climate and its variability. The ability of the models to represent these processes and reproduce their main features is therefore of crucial importance. Since both mean state and variability can occur as a result of interactions between phenomena with very different time and spatial scales, the numerical resolution of a GCM is key determinant to the ability of a model to produce realistic climate simulations. Model resolution, thus, is not a merely technical matter, but it discriminates among the processes that are involved in the simulated climate system. Therefore, it is natural that considerable attention has been spent on the investigation on how changing the numerical resolution will affect the quality of the simulation.

Though vertical and horizontal resolution are probably equally important, most of the studies have focused on the horizontal resolution. The number of papers devoted to the subject is very large starting with early work at GFDL (Manabe et al. 1970) and continuing with later studies on the impact of resolution for extended range (10-days), monthly, seasonal and longer scales (for an extended bibliography the reader is addressed to Navarra et al. 2007). These studies showed that the evaluation of the effect of resolution is often difficult as the changes in the numerics affect in a complex way the components of the models: overall the change to higher resolution is beneficial, but often it is not uniform across the model parameters and processes. The major systematic errors of a model cannot be eliminated simply by increasing resolution, even if a readjustment of the parameterization is performed (Duffy et al. 2003). Higher resolution does not appear to be a magical solution to all the illnesses of the model, but rather it defines a more advanced work field for the modeler, permitting the explicit treatment of more processes.

Within WP4.2, research activities have been carried out to explore the effects of the atmospheric model resolution (both vertical and horizontal) on the simulation of the main features of climate variability. In particular, the research has examined the impacts on the mean state and on the variability from intraseasonal to interannual timescale, for different regions of the globe, with an emphasis on the Tropics (e.g., simulation of ENSO, Asian monsoon and Tropical Cyclones). This research activity has produced a considerable number of scientific papers. In the following we provide a brief review of the main results obtained from recent works on the impact of vertical and horizontal atmospheric resolution on the simulation of the tropical climate, and we summarize the main results obtained from the studies on this subject that have been performed and published in the framework of the ENSEMBLES project .

We know this work is far from complete. In fact, important issues, such as the impacts on the mid-latitudes, or the effects of ocean model resolution are not included in this assessment. Nonetheless, we think that the results presented in this report may represent a useful tool for guiding the inclusion of higher resolution members in the ENSEMBLES Stream 2 simulations.

2. Impact of vertical resolution on the simulation of the Tropical Climate

GCM development has concentrated mostly on increasing horizontal resolution only, while the vertical resolution has received much less attention and, in general, it has been kept at approximately 20 levels, from the surface up to 10 hPa. Recently, Tompkins and Emmanuel (2000), using a single-column model, have shown that the vertical distribution of water vapour in GCMs can be very sensitive to the vertical resolution of the model. Their work questions the inclusion in GCMs of complicated parametrizations of cloud and convection if the water-vapour profile is not adequately resolved.

In recent years the interest on the possible effects of vertical resolution on climate simulation has substantially increased, as well as the number of studies facing this issue. Interestingly, the conclusions of these studies may be rather different. For example, Liess and Bengston (2004) suggest that the simulation of the MJO (Madden and Julian Oscillation) remains problematic when the vertical resolution of the model is improved, whereas Innes et al. (2001) and Pope et al. (2001) found that with the increase of the number of vertical levels, the simulated cloud spectrum and the simulated water vapour become more realistic. Furthermore, Innes et al. (2001) showed that, in their model, improvements in the cloud spectrum and water vapour vertical distribution lead to a better the simulation of the MJO. The model used in this study is the HadAM3, i.e. the atmospheric component of the Hadley Centre coupled model. With the same model, Spencer and Slingo (2003) have found that with the increase of the vertical resolution the simulation of the North Pacific response to ENSO forcing is also improved.

Land et al. (1999) have examined the impact of vertical resolution on the climatology of the ECHAM4 model at T30 horizontal resolution. In particular, they increased the number of vertical levels from 19 to 39, enhancing the model resolution especially in the middle and upper troposphere. Their findings indicate that a clear improvement cannot be observed at this horizontal resolution using 39 vertical levels instead of 19. A similar conclusion for the ECHAM5 model has been proposed by Roeckner et al. (2006), who found that the model version with 31 vertical levels performs better than the version with 19 levels, with horizontal resolutions higher than T42. This result could be explained in terms of consistency between vertical and horizontal resolution, as suggested by Lindzen and Fox- Rabinovitz (1989). Both Land et al. (1999) and Roeckner et al. (2006) based their evaluation of the model performances over the whole domain. While the previous studies on the impact of vertical resolution on the ECHAM climate have focused on the global skill of the model, the aim of this study is to analyze in detail the behaviour of the ECHAM4 model over the tropical band. We choose this region since here the convection can be strongly affected by the vertical level changes as reported by Thompkins and Emanuel (2000).

In a recent work, Ruti et al. (2006, hereafter R6) have described the mean tropical climate and its variability in the ECHAM4 model, when the vertical resolution is increased in the free troposphere, around the tropopause and in the PBL. The number of vertical levels has been increased from 19 to 42 (hereafter referred to as L19 and L42 experiments respectively). In the tropics, the L42 version satisfies the requirement of consistency between horizontal and vertical resolution in the tropics (Lindzen and Fox-Rabinovitz, 1989). The main difference between R6 and Land et al. (1999) is that in the former the number of vertical levels has been increased also in the PBL. This difference is particularly important because, as shown by Tompkins and Emanuel (2000), when the resolution in the PBL is not changed, the sensitivity of the ECHAM4 simulation to vertical resolution is reduced.

In R6 an ensembles of AMIP-like simulations performed with the L19 and L42 version of the model have been compared. The results indicate a substantial and significant improvement in the seasonal mean rainfall (not shown), mostly over the tropical Pacific, which has been explained via the impact of vertical resolution on the cloud structure. In the cloud spectrum of the L42 simulation (Figure 1a and 1b) a third peak appears at around 600 hPa, revealing that the convective parametrization starts to represent cumulus congestus clouds with tops around the 0°C level. These results are consistent with Innes et al. (2001).

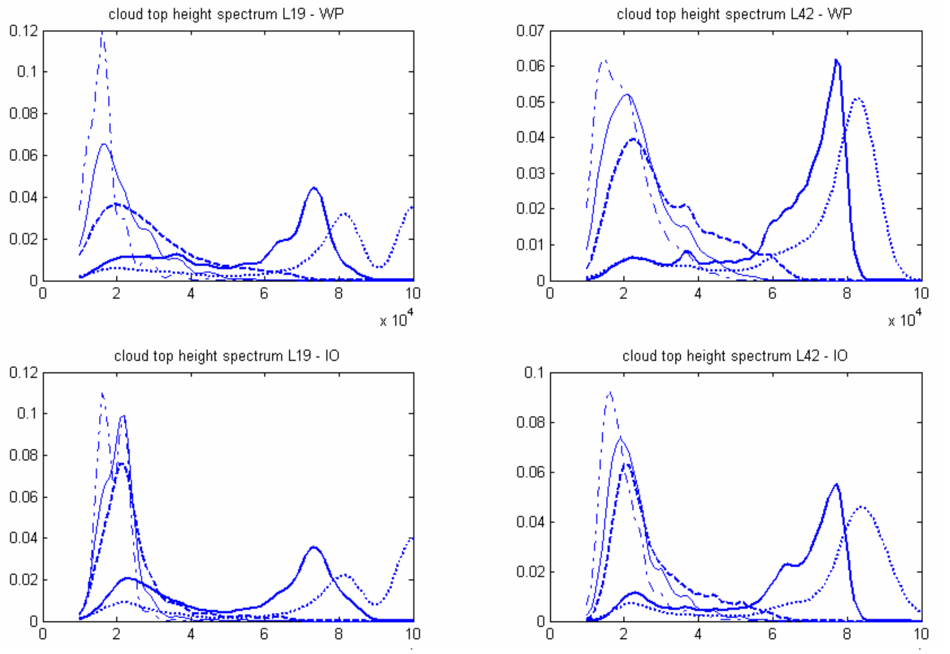

Figure 1a: Vertical distribution of grid-box winter convective cloud top for L42 (right panels) and L19 (left panels) runs. Warm Pool (upper panels) and Indian Ocean (bottom panels) area. Probability density function of cloud spectrum computed for different rainfall classes: convective rainfall < 5mm/day (thick line); 5 < convective rainfall < 10mm/day (thick dashed); 10 < convective rainfall < 15mm/day (thin line); convective rainfall > 15mm/day (dot dashed); stratiform rainfall < 5mm/day (dotted). The pdf has been computed using a kernel estimator. The kernel width is double for L42

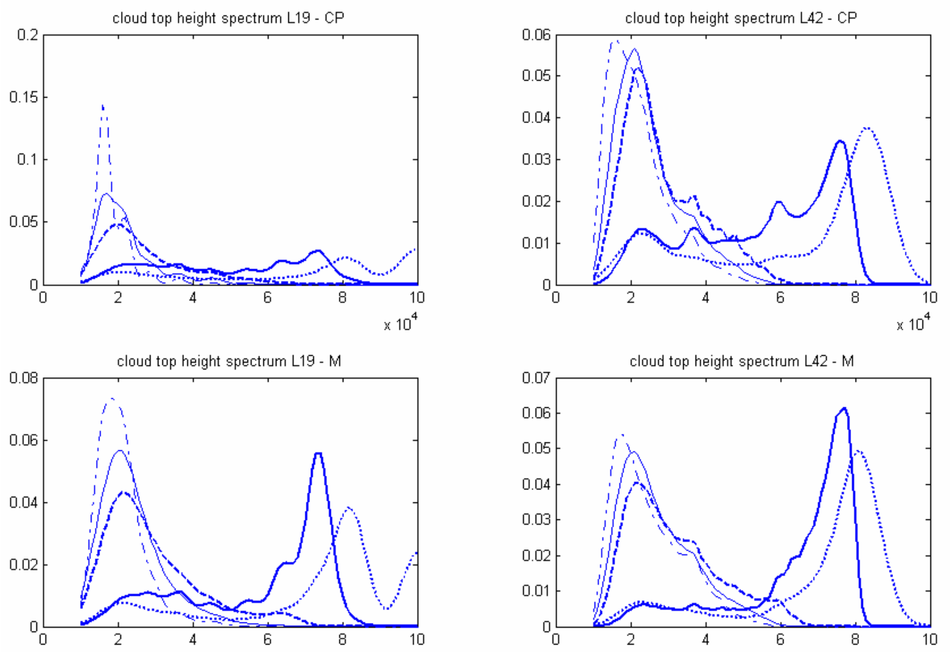

Figure 1b: Vertical distribution of grid-box summer convective cloud top for L42 (right panels) and L19 (left panels) runs. Central Pacific (upper panels) and Monsoon (bottom panels) area. Probability density function of cloud spectrum computed for different rainfall classes: convective rainfall < 5mm/day (thick line); 5 < conv. Rainfall < 10mm/day (thick dashed); 10 < conv. rainfall < 15 mm/day (thin line); conv. rainfall > 15mm/day (dot dashed); stratiform rainfall < 5mm/day (dotted). The pdf has been computed using a kernel estimator. The kernel width is double for L42.

Considering the impact of vertical resolution on the convective parametrization in a GCM, it should be noted that any convective scheme is designed mainly to represent the impacts of convection on a large-scale distribution of heating and moisture, and in turn on the tropical circulation. Therefore, in R6 also the effects on dynamics have been analyzed, considering the upper level velocity potential field and the lower tropospheric zonal wind. The change in precipitation affects the divergent field, and in turn the tropical and extra-tropical dynamics. The L42 simulation shows, for both northern winter and summer seasons, an improvement of the velocity potential (not shown) and zonal wind fields (Figure 2) over the tropical band, which, in turn, might have a beneficial impact on the extratropical variability.

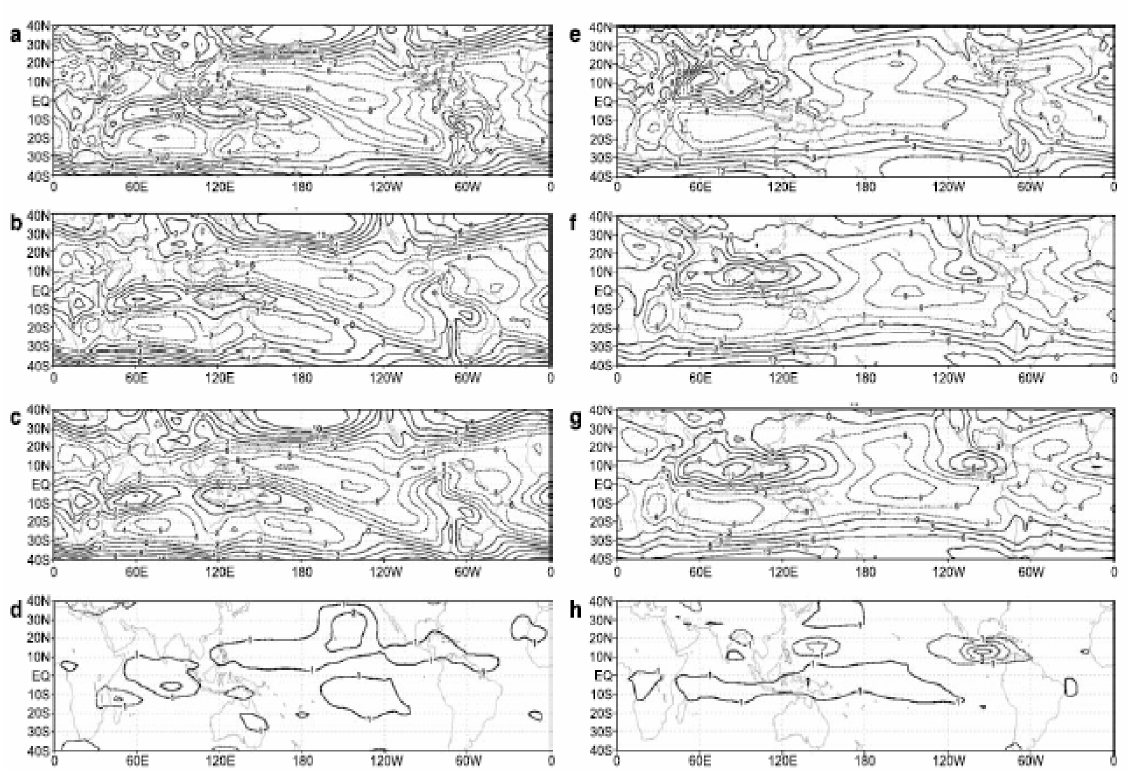

Figure 2: Winter 850-hPa zonal wind climatology (1979–95) for ERA40 (a), L42 run (b), L19 run (c), L42-L19 (d) [m/s]. The contour interval is 2m/s, but 1m/s for L42-L19. Summer 850-hPa zonal wind climatology (1979–95) for ERA40 (e), L42 run (f), L19 run (g), L42-L19 (h) [m/s]. The contour interval is 3 m/s, but 2 m/s for L42-L19. The plotted differences between the two climatologies are significant with the 99% confidence level

The difference in precipitation between the two runs, reveals a change in the heat released into the atmosphere. The heat-induced tropical circulation (Gill, 1980) difference explains the lower tropospheric zonal wind change between the L42 and the L19 simulations. Specifically, an improvement for the L42 simulation is the reproduction of a band of low-level westerlies over the equatorial Indian Ocean and the Maritime Continent (Figure 2).

The analysis has also been extended to the impact of vertical resolution to the tropical variability. What has been found is a substantial improvement in the simulation of the variability of the precipitation and of the zonal wind at 850 hPa. At intra-seasonal time scales, the increasing in the vertical resolution appears to improve the eastward and standing components of the tropical zonal wind.

The results shown and discussed in R6 contribute to the development of a dynamical framework aimed to improve our understanding of the effects that vertical resolution might have on the simulation of the general circulation. In particular, they indicate that, in general, the increased vertical resolution has beneficial effects on the simulation of the tropical climate and its variability. In particular, an analysis of the basic gross features of the tropical intraseasonal variability as described by the wavenumber-frequency spectral analysis (not shown) suggests that the L42 model reproduces a more realistic variability. However, in order to fully understand all the effects of the increased vertical resolution on specific phenomena like, for instance, the Madden-Julian Oscillation, a deeper and more detailed analysis is required.

3. Impact of horizontal resolution on the simulation of the Tropical Climate

In recent years, several papers have investigated the impact of resolution, mainly horizontal resolution, for specific processes or phenomena. Bengtsson et al. (1995) and Bengtsson et al. (2007) showed that increased horizontal resolution has beneficial impacts on the simulation of tropical cyclones. Recently, Kobayashi and Sugi (2004) have shown that the number of simulated tropical cyclones tend to increase at higher resolution. Gualdi et al. (1997) investigated the impact of resolution on the simulation of the MJO and they found that resolution alone cannot improve the accuracy of the simulation of the oscillation. The simulations of the Asian Summer Monsoon have been shown to be sensitive to horizontal resolution (Sperber et al. 1994; Stephenson et al. 1998; Kobayashi and Sugi 2004), leading to positive results at increased resolution. Horizontal resolution is also crucial to treat accurately the effects of ice sheets (Wild et al. 2003) and of Greenland orography (Junge et al. 2005).

The impact of atmospheric horizontal resolution at climate scales has received comparably less attention. Most investigations have been conducted with prescribed SST distribution for relatively short periods using observed SST (Roeckner et al. 1996; Duffy et al. 2003; Stratton 1999; Pope and Stratton 2002) or as time-slice experiments with SST from lower resolution coupled models (May and Roeckner 2001; May 2003, 2001).

There is little documentation of the effect of atmospheric resolution in coupled models. Some aspects of it were shown in Guilyardi et al. (2004) and Gualdi et al. (2005), but a more extended study at climate time scales is lacking. Here we summarize, very briefly, the main results from an analysis of the interannual climate sensitivity to atmospheric horizontal resolution performed in Navarra et al. (2007).

a. *Impact on the tropical interannual variability (ENSO)*

The focus of this paper, that for the sake of the brevity we will refer to as N7, is on the tropical coupled dynamics. The numerical set-up is such that the atmospheric model resolution is varied, but the ocean model is maintained at the same resolution. A set of simulations with the same ocean model coupled to the atmospheric model at two different horizontal resolutions have been performed. In the first the atmospheric model is truncated at spectral resolution 30 (T30) and in the second at spectral resolution 106 (T106).

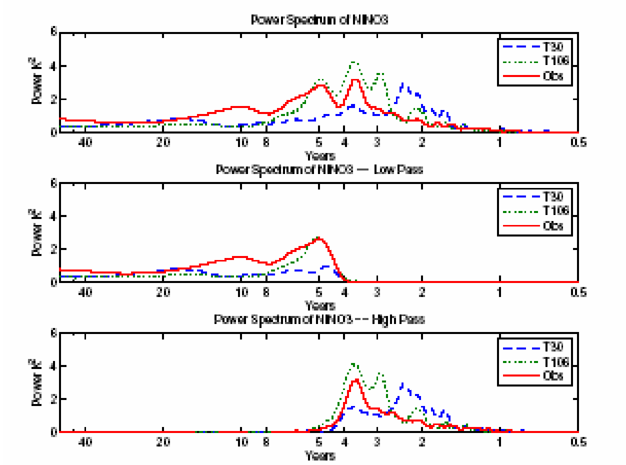

Figure 3: Power spectra of the NINO3 index for the simulations and for observations (upper panel). The middle panel are the spectra obtained with a low pass Chebyshev filter with a nominal cut off at 5 years. The lower panel is the high frequency remainder

The changes in the atmospheric resolution do affect the variability in the Tropical Pacific, even if the ocean model has not been changed at all. The impact of the horizontal resolution changes can be noted in a general indicator of the tropical variability, such as the time spectrum of the NINO3 SST index (Figure 3). The top panel of the picture shows that the coupled model with a low resolution atmosphere exhibits a marked peak of variability around two years (Guilyardi et al. 2003) and comparatively small variability everywhere else. The coupled model with the high resolution atmosphere shifts the major variability peaks toward longer time scales. The variability is overestimated with respect to the observations and there is still some remains of the misplaced peak at around two years, but there is a noticeable improvement

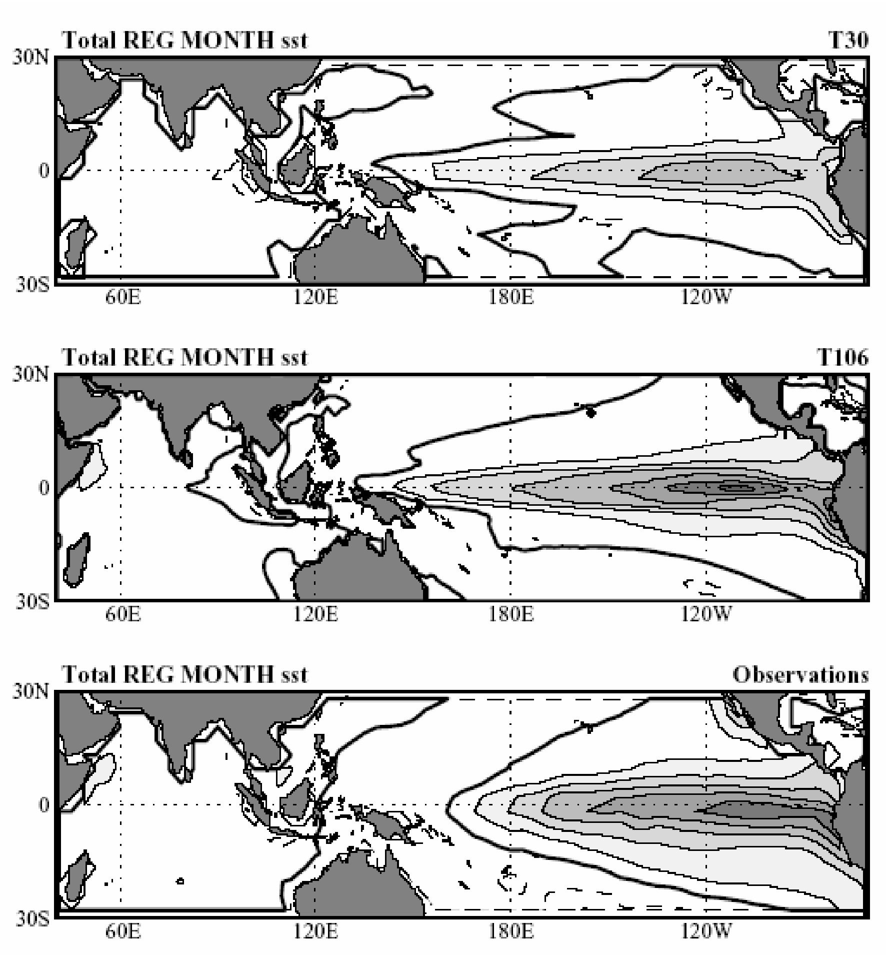

Figure. 4: Teleconnection pattern of the tropical SST expressed as a regression to the NINO3 index. Top panel, the coupled model with the T30 atmosphere, middle panel the coupled model with the T106 atmosphere and in the bottom panel the observations. The contour is 0.2 K and positive values are shaded.

The improved horizontal resolution impacts also the teleconnections properties of the variability (Figure 4). The regression pattern in the observation of the NINO3 SST index with the SST elsewhere is a wide wedge pattern protruding into the Pacific Ocean. The low resolution model displays a regression pattern that is weaker in total amplitude and it is more confined to the equator than the observations, whereas the high resolution is showing a higher amplitude and a wider pattern in latitude. Though the main systematic errors in the teleconnection are not automatically solved by the shift to high resolution, we can see that the higher resolution coupled model yields a more realistic pattern and indicate a general beneficial trend. Modifying the atmospheric resolution, therefore, affects the ocean behaviour and ocean variables even if the ocean model is not modified in the coupling.

The improvements discussed in Figure 3 and Figure 4 concern mostly the Pacific region, but certain aspects of the surface atmospheric circulation in the Indian sector that is crucial for the simulation of the summer Indian monsoon are also improved. A more detailed discussion of the effects of model resolution on the Tropical Indian ocean and monsoon system will be given in the next Section.

In N7 the comparison between the low and the high resolution model shows that at high resolution the delayed oscillator is at work in a more realistic set of parameters. The interaction between ocean and atmosphere is realized in a wider latitudinal region and not confined in a narrow strip along the equator. N7, thus, suggest that the extension of more off-equatorial regions into the coupling allows the triggering of slower off-equatorial waves that allow slower time scales and shift the dominant NINO3 variability toward longer time periods. The activation of off-equatorial Rossby waves also results in a wider, more realistic teleconnection pattern in the Pacific (see N7, Figures 10-14).

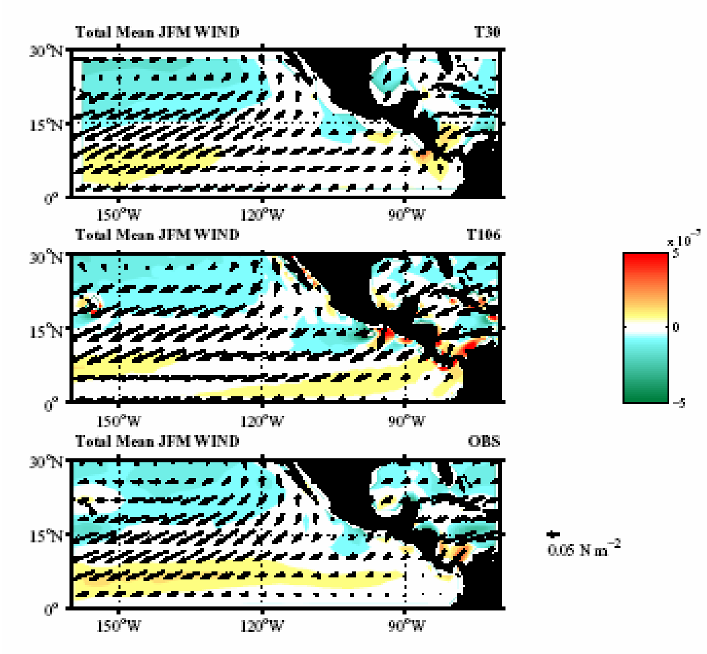

Figure 5: Surface wind stress and wind stress curl for winter (JFM) in the Mexican region. Positive values are shown in red and negative in blue, the contours are $5.\times 10^{-8} Nm^{-3}$.

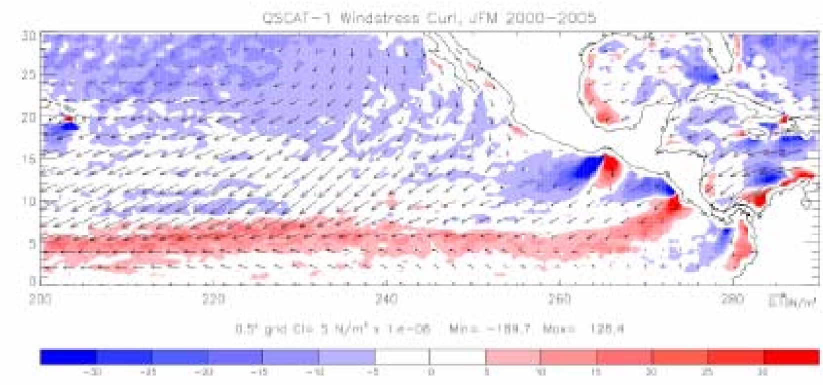

Figure 6: Surface wind stress and wind stress curl for winter (JFM) for the period 2000-2005 in the mexican region from the QuickScat surface data. Positive values are shown in red and negative in blue, the contours are $5.0 \times 10^{-8} Nm^{-3}$.

The introduction of high horizontal resolution has also other effects, related to the introduction of smaller scale mechanisms. The coastal up-welling along the South American coast is improved, reducing the systematic error in the mean SST in the East Pacific. Regions of strong curl forcing along the Mexican Pacific coast are visible in high-resolution satellite observations and are present in the T106, but totally absent in the T30 and barely hinted in the reanalysis (Figure 5 and Figure 6). They are probably linked to better resolved orographic features, creating a favorable situation to the generation of Rossby waves.

Tropical instability waves become coupled to the atmosphere, showing a clear signature pattern in the divergence field, as it has been discussed by Chelton (2005). The ocean component is producing tropical instability waves in both low and high resolution models, but the atmosphere becomes sensitive to them only in the high resolution case (Figure 7), reducing the surface‘ stresses to a more realistic value.

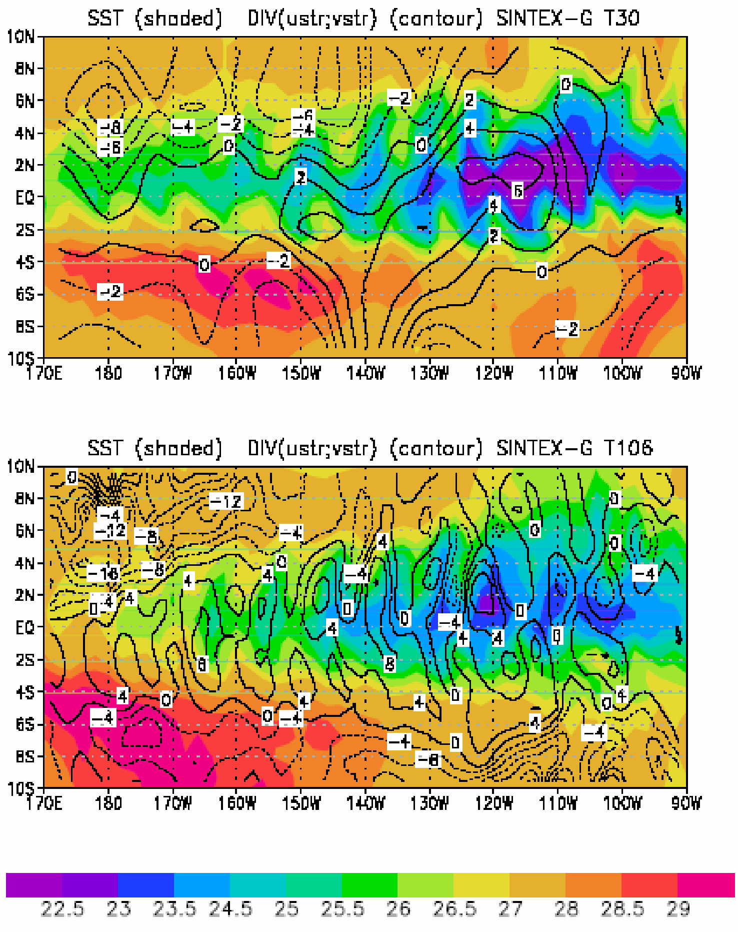

Figure 7: Snapshot of the SST (shaded) and the divergence of the surface stresses (contours) for pentads.

There is also some ground to argue that the reanalysis is showing its limitation due to relatively low resolution used, it is probably time to produce a high resolution atmospheric reanalysis data sets. Excessive surface winds seems to receive a beneficial impact from increasing atmospheric horizontal resolution.

The increase of horizontal resolution has therefore impacts on a variety of phenomenologies and it is far from being a magic bullet that fixes all the deficiencies of the models. In particular, the presence of a double ITCZ does not seem to be affected by resolution and it continues to afflict the high resolution simulation. However, high horizontal resolution seem to improve the simulations and the description of local processes.

Finally, delayed oscillator-like mechanisms appear to be the cause of the tropical Pacific interannual variability in both of the models, but in the low resolution it is confined to a narrow region close to the equator, yielding a faster period for the oscillation. The results suggest that this is probably due to the faster propagation of the waves in this area and to the weak coupling between U-stresses and SST. In the high resolution model the delayed oscillator involves a wider latitudinal extent and the U-stresses are better coupled to the SST with a mix of mechanisms that is probably closer to reality. It can also be speculated that the involvement of slower waves caused by the wider latitudinal extent of the variations in the high resolution model might lead to the spectral shift of the peak of the variability toward longer time scales.

In conclusion, the results shown in this work suggest that the increase of the atmospheric model horizontal resolution improves the simulation of the tropical climate variability, especially in the tropical Pacific, even if it does not eliminate all the major model's systematic errors, such as, for example, the double ITCZ. The improvement produced by the increased resolution seems principally due to the improved atmosphere-ocean coupling obtained with the higher resolution atmospheric model.

b. Impacts on the Asian Summer Monsoon

The Asian monsoon is a complex phenomenon and despite all the studies focused on it (e.g. Shukla, 1987; Webster et al., 1998; Annamalai et al., 1999; Fennessy et al., 1994; Ju and Slingo, 1995; Soman and Slingo, 1997), it is still not completely understood. A very important step in the analysis of the Asian monsoon and its characteristics has been the Atmospheric Model Intercomparison Project (Gates, 1992) where a set of experiments forced with observed SST from 1979 to 1994 has been built with different AGCMs. The analysis of those experiments revealed that the simulation of the basic aspects of the monsoon needs further improvements, and that only few models are able to capture the fluctuations between good and poor monsoon seasons in a realistic way (Sperber and Palmer, 1996).

The Echam4 atmospheric general circulation model is used to create experiments forced with observed SST from 1956 to 1999 (Amip-type experiments) interpolated from the HadISST dataset (Rayner et al., 2000). The availability of three different horizontal resolutions (T30, T42 and T106) permits to analyze the sensitivity of the model simulations to the horizontal resolution.

Furthermore, the SINTEX CGCM has been integrated with the atmosphere at three different horizontal resolutions (T30, T42 and T106). Gualdi et al.(2003) used those experiments to study the impact of the horizontal resolution on the tropical climate variability.

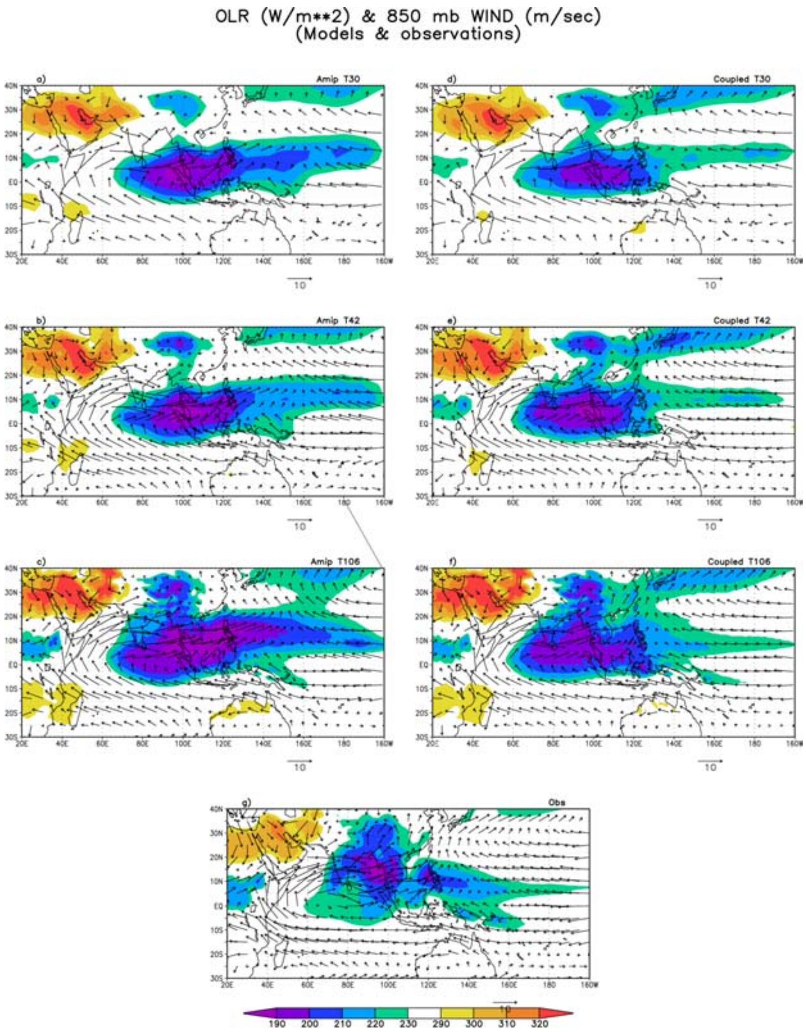

Figure 8: Mean JJA OLR (W/m2) and surface wind vectors (m/sec) for the Echam4 AMIP-type experiments (panels a,b,c) and the SINTEX coupled model experiments (panels d,e,f) at three different resolutions (T30, T42 and T106), and for the observations (panel g). OLR data are from NOAA dataset and winds from ERA40 reanalysis.

The same experiments have been analyzed to study the differences on the Asian monsoon simulation imposed by an interactive ocean.

To investigate with more details the influence of the interaction between atmosphere and ocean a set of experiments with Echam4 forced by SST obtained as a result of the coupled model simulation has been performed.

The monsoon and its main features are generally studied through the analysis of precipitation and wind fields. In Figure 8 the mean JJAS wind at 850 mb is superimposed to the mean JJAS OLR (Outgoing Longwave Radiation), which may be considered a proxy for convection. One of the most dramatic elements of the Asian summer monsoon is the development of the lower tropospheric Somali Jet in response to the land-sea gradient of large-scale heating (Sperber et al., 2000).

The seasonal reverse in direction and the intensification of the low-level wind are well captured by the atmospheric model at all resolutions (Figure 8a-b-c). In general even the low-resolution Echam4 GCM has a good representation of the Asian summer monsoon mainly for circulation features (Cherchi and Navarra, 2003). One of the main biases of the atmosphere-only model is the simulation of the south-westerly flow while crossing the Equator. In particular, in the Amip-type experiments at all resolutions (Figure 8a-b-c), the meridional component of the flow is too strong at the Equator. In the coupled model experiments (Figure 8d-e-f) this bias is less evident, mainly at higher resolution.

After the monsoon onset the low level westerly flow expands from the Indian subcontinent toward China reaching the western Pacific Ocean, as a manifestation of the Western North Pacific High (Wang et al., 2001). This behaviour is quite well simulated by the Echam4 model even if the intensity of the winds is larger than in the observations (Figure 8 a-b-c). The East Asian Summer Monsoon (EASM) region is characterized by lower level easterly winds from the Pacific Ocean and westerly from the Maritime Continents region, while in the model the main flow comes from the Pacific Ocean producing a somewhat poor simulation of this component of the Asian-Pacific monsoon.

In the coupled model experiments (Figure 8d-e-f), along South East Asia the wind direction is well simulated, while its intensity is underestimated. The areas with OLR less than 200 W/m^2 (blue-shaded in the figure) are identified as heating sources and are indicative of convection centres, while regions of maxima OLR (values greater than 290 W/m^2 are red-shaded in the figure) indicate irradiative loss to space. From the observations (Figure 8g) two main convection centres may be identified: one is located in the Bay of Bengal and the other in the vicinity of Philippines.

At low resolution (Figure 8a, d), the low values of OLR are located too much south with respect to the observations, with the minima located around 100˚E. At T106 resolution the areas with OLR lower than 220 W/m^2 are shifted slightly eastward and southward, assuming a pattern more similar to satellite data (Figure 8c, f). In all the experiments, the OLR over Indonesia is lower than observed, producing enhanced convection in that area. The lack of convection over the Bay of Bengal remains a major deficiency in the simulation of the Asian summer monsoon, even at T106 resolution. The main differences between the coupled and the Amip-type experiments results are around the Philippines, where the coupled model has higher OLR, suggesting the simulation of lower than observed precipitation in that area.

SST is an important forcing for the Asian summer monsoon; in particular the relationship between SST in the Tropical Pacific Ocean and the Indian summer monsoon is well recognized (Webster and Yang, 1992; Ju and Slingo, 1995; Soman and Slingo, 1997; Kinter et al., 2002). Figure 9a shows the mean summer SST observed. In the northern tropical Indian Ocean, summer SST warms up, except in the western part of the basin near the coast of Somalia, where cold water from the below up-wells producing a strong gradient.

In the coupled model, SST in the Tropical Indian Ocean is warmer than observed, particularly north of the Equator (Figure 9b, c, d). For instance, in the north-western Indian Ocean SST in the coupled model experiments is 1-1.5˚C warmer than the HadISST values, and the up-welling region in the western part of the basin is not simulated. In the Equatorial Pacific ocean the cold tongue regime simulated by the model extends too westward (Guilyardi et al., 2003). This bias may be responsible for a worse simulation of the connection between ENSO and the monsoon (Terray et al., 2005). In the North Eastern Tropical Pacific Ocean the simulated SST is colder than observed, especially at lower resolutions (Figure 9b, c), and this may be associated to the weaker representation of the surface winds and precipitation in the western north Pacific monsoon region.

In some regions (i.e. Western Ghats, Bay of Bengal, Western Equatorial Indian Ocean and Indonesia) the coupled model simulates more precipitation with respect to the atmospheric model alone, whereas in others (i.e. Eastern Equatorial Indian Ocean and north-western tropical Pacific Ocean) it simulates less precipitation.

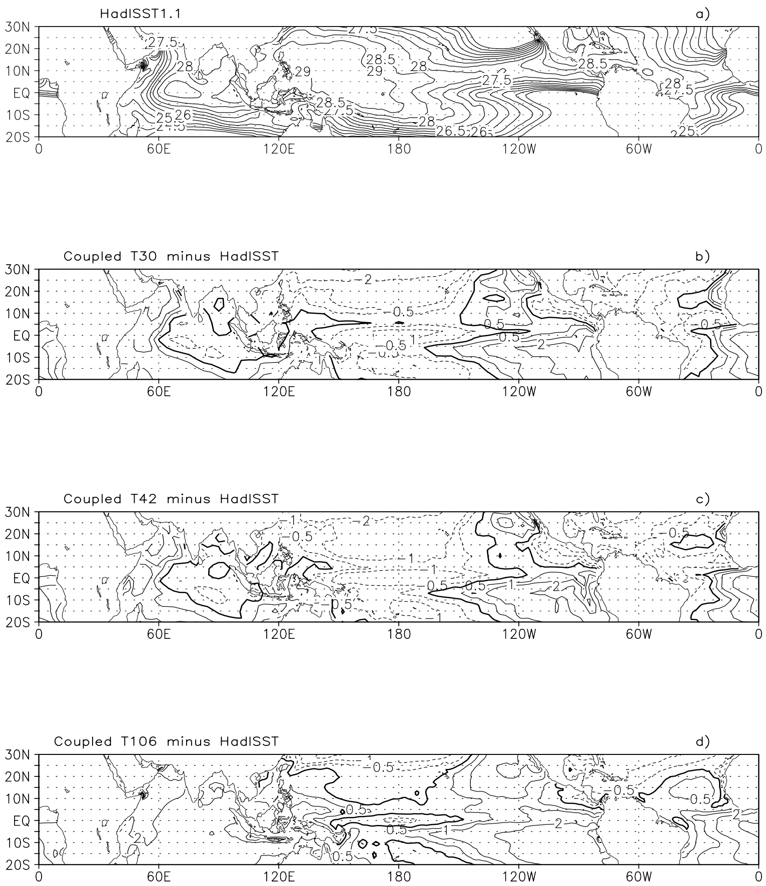

Figure 9: Mean JJA SST (˚C) from the HadISST dataset (a), used to forced the atmospheric model. The observed field has been subtracted from the coupled model results at T30, T42 and T106 (b, c, d, respectively). Contour intervals are -4, -2, -1, -0.5, 0.5, 1, 2 , 4, 6˚C. The thicker line corresponds to the zero contour.

To analyze with more details the effective role of the SST, a new set of experiments has been built with the atmospheric model forced by SST obtained from the coupled model simulations. The experiments have been performed for each horizontal resolution and integrated for 10 years.

The Echam4 model when forced by SST with a warm bias in the Indian Ocean and with a cold bias in the North Western Pacific Ocean simulates a south Asian summer monsoon with more rainfall in the Bay of Bengal and in the Indian subcontinent, and with less rainfall in the Eastern Equatorial Pacific Ocean and in the North Western Pacific Ocean. The south-westerly flow in the Indian ocean is weaker in the new experiments (not shown). In particular, both the zonal and the meridional components are weaker in the Equatorial band and just south of its, and they are stronger north of it in correspondence of the Indian subcontinent and of South East Asia.

The differences between the coupled model simulations and the results from the forced experiments are rather small, suggesting that in the coupled model the bias in the SST is the dominant influence.

ENSO is known to be an important forcing of the interannual variability of the Asian summer monsoon (Webster et al., 1998; Sperber et al., 2000). Warm ENSO events are generally related to dry monsoon seasons, with cold ENSO events associated with wet monsoon seasons (Rasmusson and Carpenter, 1983; Zhang et al., 1996; Lau and Nath, 2000; Kinter et al., 2002). The warm episodes of ENSO are associated with a shift in the climatological Walker circulation to the Eastern Pacific. This shift results in enhanced low-level convergence over the Equatorial Indian Ocean and in driving an anomalous Hadley circulation with descent over the Indian continent and decreased monsoon rainfall (Goswami, 1998).

There are evidences that in last decades the connection between ENSO and the monsoon has decreased (Kumar et al., 1999b). Changes in this connection may be associated to changes in the Tropical North Pacific Ocean climate and in the low-level circulation with centres in the South China Sea and Philippines Islands (Kinter et al., 2002). In particular, Kinter et al.(2002) evidenced that the relationship between monsoon and ENSO has weakened after the1976 climate shift.

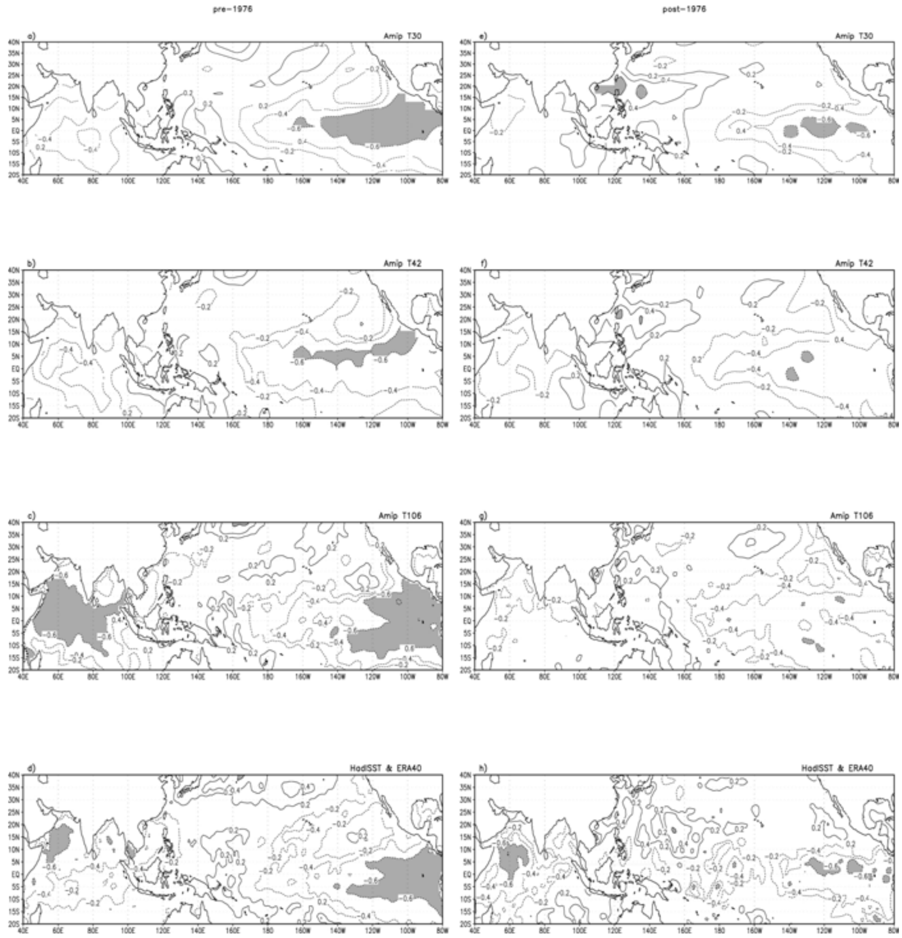

Figure 10: Correlation maps of JJA mean SST and DMI for the Echam4 Amip-type experiments and the reanalysis. Left panels for the period before 1976 and right panels for the period after 1976. Shaded values are lower than -0.6 and higher than 0.6.

The maps of the correlation coefficients of the Dynamical Monsoon Index (DMI) with global SSTs have been computed (Figure 10) for the AMIP-type experiments in two different periods: before 1976 (from 1956 to 1976) and after 1976 (from 1977 to 1999) to investigate the effects of those changes in the atmospheric model.

The DMI is a dynamical index defined by Webster and Yang (1992) as the mean JJA zonal wind shear (u850-u200) on the area 40-110E, Eq-20N, and it has been used in many studies (e.g. Ju and Slingo,1995; Li and Yanai, 1996; Lau et al., 2000) to represent the broad scale features of the Asian monsoon. The DMI simulated by the Echam4 model is significantly correlated with the observations at all resolutions.

SST is a fundamental and important oceanic indicator of the ENSO process (Kinter et al., 2002) and JJA is the season where the connection is established and strong (Kumar et al., 1999a). The correlation field (Figure 10h) is characterized by the horseshoe pattern over the Pacific Ocean (as defined by Miyakoda et al., 1999). To the west the horseshoe pattern is surrounded by a region of opposite sign and it is connected with other correlations over the Indian Ocean. In the Amip-type experiments (Figure 10a-b-c) the pattern described is realistically captured at all resolutions. It is noteworthy that DMI and Eastern Equatorial Pacific SSTs have a strong negative correlation. This result supports the idea that the DMI may represent the large-scale circulation changes over the Indian Ocean associated with ENSO (Goswami et al., 1999). From the picture it is evident that the correlation has decreased after 1976 (Figure 10e-f-g-h). The decrease of the correlation in the Eastern Equatorial Pacific Ocean is associated with a decrease of the negative correlation in the Indian Ocean and with an increase of the positive correlation in the Western Tropical Pacific Ocean.

The analysis of the precipitation before and after 1976 in the model results reveals that in correspondence of a weakening of the relationship between Asian summer monsoon and ENSO there is a weakening (down to 3-4 mm/day) of the rainfall amount in the Indian subcontinent and in the Bay of Bengal, and an intensification (up to 6-8 mm/day) of the precipitation in the Western North Pacific Ocean (not shown). The same behaviour is simulated at all the resolutions considered.

In summary, Cherchi and Navarra (2007) have shown that the increase of the atmospheric resolution has beneficial impacts also on the simulation of the Asian summer monsoon. Particularly, the main improvements are associated to regional aspects of the precipitation, for example the Western Ghats precipitation is better reproduced. The interannual variability of precipitation and wind fields in the Asian monsoon region appears to be less affected by an increase in the horizontal resolution than the mean climatology is. A possible reason is that the former is mainly SST-forced. Besides, the availability of experiments at different horizontal resolution realized with the Echam4 model coupled to a global oceanic model allows the possibility to compare these simulations with the experiments previously described. This analysis showed also that the coupled model is able to reproduce a realistic monsoon, as the basic dynamics of the phenomenon is captured. The increase of the horizontal resolution of the atmospheric component influences the simulated monsoon with the same characteristics of the forced experiments.

c. Impact on the simulation of the Tropical Cyclones and its implications on Climate Change studies

The sensitivity of the simulation of tropical cyclones (TC) to resolution was investigated with the Max Planck Institute (MPI) coupled (ECHAM5/MPIOM) and atmosphere (ECHAM5) climate models. Three different atmospheric resolutions were considered: T63, T213, and T319; all with 31 vertical levels. TC were analysed using a newly developed tracking algorithm, which identifies storms using three parameters: maximum relative vorticity at the storm center, relative vorticity vertical gradient, and storm duration. The parameter values were chosen using ERA40 reanalysis data.

The intensity and size of the TC depend crucially on resolution with higher wind speed and smaller scales at the higher resolutions. The typical size of the TC is reduced by a factor of 2.3 from T63 to T319 using the distance of the maximum wind speed from the centre of the storm as a measure. The full three dimensional structure of the storms becomes increasingly more realistic as the resolution is increased. These improvements with resolution are illustrated by tangential and radial wind composites at storm maximum (Figure 11). For the tangential wind it is apparent that the west-east asymmetry exists through the depth of the storm with the highest winds to the east. These occur at a radial distance of 3.50 for the T63 resolution, 1.50 for T213 and a little less than this for T319. It is also apparent that the maximum wind speed increases with resolution from ~24ms-1 for T63 to ~50ms-1 for T319. The radial winds (Figure 11) clearly show the south-north asymmetry with inflow to the south and outflow to the north, this pattern persisting throughout the depth of the composite storm. This pattern clearly becomes more pronounced with resolution, in particular for the outflow. The warm core structure of the TC also improves with resolution: the temperature anomaly increases from ~2.50K at 300hPa for T63 to ~8.0K for T319.

The dependence of TC simulation on resolution has important implications for the projected changes in future TC activity obtained from low resolution models. This dependence was investigated in climate change scenario simulations with MPIOM/ECHAM5 coupled (T63) and ECHAM5 uncoupled time-slice (T213/T319) simulations. At T63 resolution, a 20% reduction in the number of the TC in the 21st century relative to the 20th century is simulated, but no change in the number of the more intense storms was seen. The reduction in the number of storms occurs in all regions. At T213 resolution, there was a 10% reduction in the number of simulated TC in the 21st century compared to the 20th century. However, unlike at T63 resolution, there was a marked increase in the number of intense storms, with the number of storms with maximum wind speeds greater than 50ms^{-1} increases by a third. Most of the intensification takes place in the Eastern Pacific and in the Atlantic where also the number of storms more or less stays the same. Similar results were obtained at T319 resolution. The results of this analysis have been submitted for publication in Tellus (Bengtsson et al., 2007)

4. Summary

The main objective of this report is to give an assessment of the possible impacts of model resolution on the characteristics of the simulated climate and variability. To this goal, we have summarized very succinctly the main results obtained from the research activity performed on this subject in WP4.2 and from recent studies reported in the literature.

The studies considered in this report have concentrated mostly on the effects of model resolution in the tropical regions. Further work is required to extend this analysis to extra-tropical regions.

The findings indicate that, in general, the increased resolution, both vertical and horizontal, has beneficial effects on the simulation of the tropical climate and its variability. Specifically, in the case of

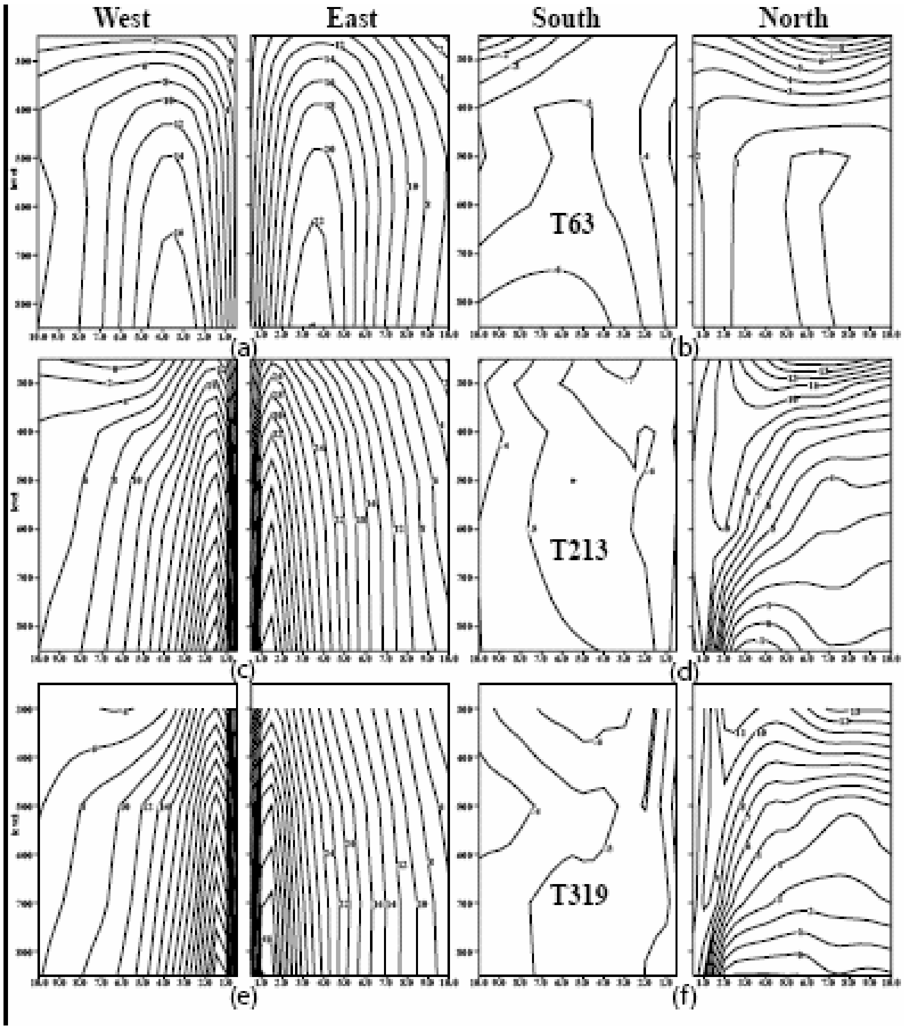

Figure 11: Cross sections of tangential and radial wind component composites for the 100 most intense storms for each of the resolutions used, T63, T213 and T319, (a) west to east, T63 tangential component, (b) south to north, T63 radial component, (c) west to east, T213 tangential component, (d) south to north, T213 radial component, (e) west to east, T319 tangential component, (f) south to north, T319 radial component. Wind speeds in ms-1, bold line every 10ms-1 for tangential winds and every 5ms-1 for radial winds.

increased vertical resolution, the results show improvements in the convective scheme performance and in the related dynamic fields over the Tropics. The improvement of the simulated rainfall when the number of vertical levels is increased has been explained via the impact of vertical resolution on the cloud structure. In the cloud spectrum of the high-resolution simulation, a third peak appears around 600 hPa, revealing that with high vertical resolution the convective parametrization starts to represent *cumulus congestus* clouds, which, on the other hand, are absent in low vertical resolution models.

Also the increase of horizontal resolution appears to be in general beneficial, even if it does not eliminate all the major systematic errors of the models. For example: in a series of simulations performed with the SINTEX coupled GCM, the unrealistic two-year peak dominating the ENSO variability obtained with low atmospheric resolution (T30) appears to be significantly moderated at higher resolution (T106), as it shifts to longer time scale. At high resolution new processes come into play, as the coupling of tropical instability waves, the resolution of coastal flows at the Pacific Mexican coasts and improved coastal forcing along the coast of South America. The delayed oscillator seems the main mechanism that generates the interannual variability both at high and low resolution, but the models realize it in different ways. In the T30 model it is confined close to the equator, involving relatively fast equatorial and near-equatorial modes, in the high resolution, it involves a wider latitudinal region and slower waves. It is speculated that the extent of the region that is involved in the interannual variability may be linked to the time scale of the variability itself.

We know this work is not exhaustive of the subject matter. To this aim further work is required, including important aspects disregarded here, such as, for example, the impacts on the extra-tropics and the effects of the oceanic resolution. However, tough far from complete, we think this report may provide some help to guide the inclusion of higher resolution members in the ENSEMBLES Stream 2 simulations.

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