Statement on Tropical Cyclones and Climate Change

This statement was authored by participants of the WMO International Workshop on Tropical Cyclones, IWTC-6, San Jose, Costa Rica, November 2006. This resulted from discussion and review through the two weeks of the workshop. The process was overseen by the WMO Tropical Meteorology Research Programme TMRP Committee TC2: Impact of Climate Change on Tropical Cyclones. Membership: John McBride (Australia, Committee Chair); Kerry Emanuel, Thomas Knutson, Chris Landsea, Greg Holland, Hugh Willoughby (USA); Johnny Chan, C-Y Lam (Hong Kong, China); Julian Heming (United Kingdom), Jeff Kepert (Australia).

1. This statement was developed, discussed and endorsed at the World Meteorological Organization (WMO) Sixth International Workshop on Tropical Cyclones, San Jose Costa Rica, November 2006. These invitation-only WMO International Tropical Cyclone Workshops are held every four years to bring together researchers and practitioners in the field of tropical cyclone forecasting. The Sixth Workshop was attended by 125 delegates from 34 different countries and regions. The Statement has been requested by WMO leadership and many heads of National Meteorological and Hydrological Services so they can respond to questions from the media, and also to assist in advising their governments on future activities and how to respond to climate change effects.

PURPOSE:

2. To provide an updated assessment of the current state of knowledge of the impact of anthropogenically induced climate change on tropical cyclones.

BACKGROUND MATERIAL:

3. The International Workshop on Tropical Cyclones series are organised by the Tropical Meteorology Research Program (TMRP) of the WMO Commission for the Atmospheric Sciences. Subcommittees of the TMRP have previously produced two statements on tropical cyclones and climate change. One of these has been published in the refereed literature: Henderson Sellers et al. (1998). The other (TMRP, 2006) was presented at the February 2006 fourteenth meeting of the Commission for the Atmospheric Sciences, in response to the high level of international publicity on the topic arising from the severe northern hemisphere hurricane season of 2005, which included the disaster associated with Hurricane Katrina. What was significant about the February 2006 statement is that the authors included prominent scientists from both sides of the recent debates that appear in the literature and at conferences.

4. This current statement draws on the contents of these previous statements. In addition, as preparation for the sixth IWTC in Costa Rica, international working groups were formed to review recent progress on all aspects of tropical cyclone research. These were distributed one month prior to the Workshop and are published as the WMO technical Report series (WMO, 2006). The current statement borrows freely from these Working Group Reports. In particular one of these reports (Knutson et al, 2006a) is a review of research progress on “Possible relationships between Climate Change and Tropical Cyclone Activity”. Both the main statement and the summary were developed by the Workshop Participants during the course of the 2-week international workshop.

5. In this document, the term "tropical cyclone" is used as the generic name for a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and a definite cyclonic surface wind circulation (following Holland, 1993). The term includes systems referred to as tropical storms in some parts of the world as well as the systems called hurricanes and typhoons. These latter systems (hurricane, typhoon) are regionally specific names for a strong or intense tropical cyclone. Tropical cyclone intensity is primarily recorded in observational databases as the maximum sustained [either 1 min or 10 min] surface winds. The maximum wind observation is averaged over either 1 minute or 10 minutes, depending on the region of the globe.

CURRENT UNDERSTANDING OF THE IMPACT OF CLIMATE CHANGE ON TROPICAL CYCLONE ACTIVITY

6. The climatological conditions under which tropical cyclones occur have been well established over decades of research. These include a requirement for warm sea surface temperatures, low vertical wind shear and high values of large scale relative vorticity in the lower layers of the troposphere (Gray, 1968, 1975; McBride, 1995).

7. It is also well established observationally that over the past several decades the sea surface temperatures over most tropical ocean basins have increased in magnitude by between 0.25 – 0.5 degrees C (e.g., Webster et al. 2005; Santer et al., 2006).

8. It is well accepted by most researchers within the field of climate science that the most likely primary cause of the observed increase of global mean surface temperature is a long term increase in greenhouse gas concentrations (IPCC, 2001; IADAG 2005). It is likely that most tropical ocean basins have warmed significantly due to this same cause (Santer et al., 2006; Knutson et al., 2006b; Karoly and Wu, 2005). If anthropogenic increases in greenhouse gases are the primary cause, then it would be expected that tropical sea surface temperatures will increase by an even greater amount in the 21st century than during the 20th century, as described in the climate projections of the IPCC (2001).

9. Globally the major factor affecting tropical cyclone frequency and tracks on an interannual (e.g., 2-7 year) time scale is the ENSO phenomenon. This has been shown to affect the genesis regions and the subsequent motion in all tropical cyclone basins (Nicholls, 1979, 1984; Chan, 1985, 2000; Gray and Sheaffer, 1991; Landsea et al., 1999; Irwin and Davis, 1999; Chia and Ropelewski, 2002; Wang and Chan 2002; Chu, 2005; Ho et al., 2006). On the interannual time-scale, there is no established in-situ positive relationship between sea surface temperature and tropical cyclone frequency (Nicholls, 1984; Raper, 1992; Chan and Liu, 2004) The exception to this is the North Atlantic, where it is well established that sea surface temperature is one of the factors impacting on the number and severity of cyclones (Shapiro, 1982, Raper 1992, Shapiro and Goldenberg, 1998, Landsea et al., 1998). No such in-situ relationship has been established for the other cyclone basins.

10. During 2005 two highly publicised scientific papers appeared documenting evidence from the observational record for an increase in tropical cyclone activity. Emanuel

(2005) has produced evidence for a substantial increase in the power of tropical cyclones (denoted by the integral of the cube of the maximum winds over time) for the West Pacific and Atlantic basins during the last 50 years. This result is supported by the findings of Webster et al (2005) that there has been a substantial global increase (nearly 100%) in the proportion of the most severe tropical cyclones (category 4 and 5 on the Saffir-Simpson scale), from the period from 1975 to 2004, which has been accompanied by a similar decrease in weaker systems. Mann and Emanuel (2006) reported that tropical cyclone counts in the Atlantic closely track low-frequency variations in tropical Atlantic SSTs, including a long-term increase since the late 1800s and early 1900s.

11. A number of authors attribute the reported increases as being due primarily to data reliability issues, in that the strong tropical cyclones are more accurately monitored in the recent years. Numerous tropical cyclones may have been missed and not counted even in the Atlantic basin, especially prior to 1910 (Landsea et al. ,2004, 2006 and Landsea, 2005). The historical record of tropical cyclone tracks and intensities is a by-product of real-time operations. Thus its accuracy and completeness changes continuously through the record as a result of the continuous changes and improvements in data density and quality, changes in satellite remote sensing retrieval and dissemination, and changes in training. Current estimates of tropical cyclone intensity are highly dependent on a satellite imagery interpretation technique, known as the Dvorak technique (Velden et al, 2006). Consistent with this, a step-function change in methodologies for determination of satellite intensity around the globe occurred with the introduction of geosynchronous satellites in the mid to late 1970’s. Further changes in methodologies occurred through the 1980’s as satellite instrumentation changed and as the technique evolved. Klotzbach (2006) restricted his analysis to the last 20 years when there were consistent satellite imagery and found no significant change in global net tropical cyclone activity and a small trend (~+10%) in category 4 and 5 frequencies. Kamahori et al. (2006) – using the Japanese Meteorological Agency (JMA) typhoon database – found that there was a substantial drop in the amount of category 4 and 5 typhoon activity between the periods 1977-1990 and 1991-2004, which is in contrast to the Webster et al. (2005) study that utilized the Joint Typhoon Warning Center (JTWC) typhoon database. Undoubtedly, this discrepancy relates to JMA vs JTWC satellite treatment of tropical cyclone intensities once aircraft reconnaissance was discontinued there in 1987. Chan (2006) extended the analysis of Webster et al for the Northwest Pacific basin back to earlier years and argued that the trend in that basin is part of a large inter-decadal variation, similarly to what Goldenberg et al. (2001) argue for the Atlantic basin.

12. In the Atlantic basin, where the most reliable historical hurricane records are believed to exist, the causes of the pronounced multidecadal variability of major hurricane activity in recent decades is currently being debated. Goldenberg et al. (2001) argue that Atlantic major hurricane activity is oscillatory, being modulated (via vertical wind shear and other circulation changes) by a multidecadal mode of SST variability referred to as the Atlantic Multidecadal Oscillation. Mann and Emanuel (2006) dispute this claim, attributing decadal changes in tropical Atlantic sea surface temperature to variations in radiative forcing caused by varying solar activity, volcanic and manmade aerosols, and greenhouse gases. Expectations about future trends vs cyclical variations of Atlantic hurricane activity would be quite different

depending upon the relative importance of these two proposed factors in explaining Atlantic tropical cyclone variations in recent decades.

13. The scientific debate concerning the Webster et al and Emanuel papers is not as to whether global warming can cause a trend in tropical cyclone intensities. The more relevant question is how large a change: a relatively small one several decades into the future or large changes occurring today? Currently published theory and numerical modeling results suggest the former, which is inconsistent with the observational studies of Emanuel (2005) and Webster et al. (2005) by a factor of 5 to 8 (for the Emanuel study). The debate is on this important quantification as to whether such a signal can be detected in the historical data base, and whether it is possible to isolate the forced response of the climate system in the presence of substantial decadal and multi-decadal natural variability. This is still hotly debated area for which we can provide no definitive conclusion.

14. Through the work of many researchers (Emanuel 1999, Emanuel et al. 2004, Free et al. 2004, Holland 1987, Holland 1997, Tonkin et al. 2000, Persing and Montgomery 2003, Montgomery et al. 2006) there is a developing theory governing maximum tropical cyclone intensity. The key concept is that for a given ocean temperature and atmospheric thermodynamic environment there is an upper bound on the intensity a tropical cyclone may achieve. This upper bound is referred to as the Maximum Potential Intensity (or MPI). As discussed in the papers by Emanuel, Holland and collaborators, few tropical cyclones actually achieve their MPI, as before such a state can be achieved they make landfall, recurve, undergo an unfavourable atmospheric environment (such as vertical wind shear) or experience an unfavourable thermal structure of the upper ocean. Emanuel (1987) and Tonkin et al (1997) presented evidence that CO2 induced climate change would bring about a substantial increase in the MPI of tropical cyclones around the globe. Knutson and Tuleya's (2004) idealized hurricane model experiments support the theoretical predictions of the MPI theory in the context of CO2-induced climate warming. Given, however, that only a small percentage of tropical cyclones attain their MPI and that the sensitivity of hurricane intensity to CO2-induced warming is 3-5% per degree Celsius in these simulations and theories, Knutson and Tuleya (2004) have speculated that CO2 induced tropical cyclone intensity changes are unlikely to be detectable in historic observations and will probably not be detectable for decades to come.

15. Climate models (global and regional) remain an important tool for investigating tropical cyclone variability and change. These contain hypotheses for how the climate system works, in a framework which allows experiments to be performed to test various hypotheses or compare models' historical simulations against historical observations. The models can provide physically based scenarios of future climate change for large-scale fields (e.g., SST, MPI, large-scale wind fields) of relevance to tropical cyclone activity. However, the uncertainty associated with future projections from climate models is generally larger for the regional scale phenomena of importance to tropical cyclone activity (e.g., El Niño) than for such measures as global mean temperature. Even for global mean temperature, uncertainties in future projections are substantial (e.g., IPCC 2001) owing to uncertainties in such factors as future anthropogenic emissions of greenhouse gases, global and regional climate sensitivity (e.g., cloud feedback), indirect aerosol forcing, and ocean heat uptake. The notion of substantial 21st century climate warming appears to be robust to these

uncertainties (IPCC 2001) although the magnitude of the warming still has large uncertainties.

16. Currently there is large overall uncertainty in future changes in tropical cyclone frequency as projected by climate models with future greenhouse gases. The most recent results obtained from medium and high resolution GCM indicate a consistent signal of fewer tropical cyclones globally in a warmer climate (Sugi et al., 2002; McDonald et al., 2005; Bengtsson et al., 2006; Oouchi et al., 2006) , with some regions showing increases in some simulations, though these findings are still not conclusive. Based on the model simulations, the broad geographic regions of cyclogenesis and therefore also the regions affected by tropical cyclones are not expected to change significantly. Most models used for such global warming experiments have not been examined extensively concerning their ability to reproduce known historical variations (interannual to interdecadal) in tropical cyclone activity in various basins. While these models generally produce weak tropical cyclone-like storms in roughly the correct locations and seasons, many in the hurricane research community are sceptical of the tropical cyclogenesis process in these low-resolution models, which calls into question the reliability of their future projections.

17. Concerning future changes in tropical cyclone intensity, there is substantial disagreement among recent global and regional climate modelling studies, although the highest resolution models available show evidence for some increase in intensity (Oouchi et al, 2006; Walsh et al., 2004), in support of both potential intensity theory and idealized hurricane model simulations. A limitation of the climate models used thus far is that the simulated tropical cyclones are substantially weaker than observed—and dramatically so for the lower resolution models—and the models have not demonstrated that they can reproduce the observed increase of attainable tropical cyclone intensities with increasing SST. In cases where this relationship has been examined (e.g., Yoshimura et al. 2006) the dependence is much weaker than observed.

18. Given the consistency between high resolution global models, regional hurricane models and MPI theories, it is likely that some increase in tropical cyclone intensity will occur if the climate continues to warm.

19. A robust result in model simulations of tropical cyclones in a warmer climate is that there will be an increase in precipitation associated with these systems (Knutson and Tuleya, 2004; Hasegawa and Emori, 2005; Chauvin et al., 2006; Yoshimura et al., 2006). The mechanism is simply that as the water vapor content of the tropical atmosphere increases, the moisture convergence for a given amount of dynamical convergence is enhanced. This should increase rainfall rates in systems (viz tropical cyclones) where moisture convergence is an important component of the water vapor budget. The only observational study addressing tropical cyclone -rainfall variations is that by Groisman et al. (2004) for the United States, which showed substantial multidecadal variability but no long-term trend in total tropical cyclone -related rainfall, a metric which they stated was primarily related to the frequency of tropical cycloness. Other measures such as per-cyclone precipitation intensity at landfall were not assessed. Groisman et al. did report a significant increase (26% per 100 yr) in the annual frequency of very heavy precipitation *unrelated* to tropical cyclones in the

southeast coastal U.S. Until further observational studies are carried out on observed trends in tropical cyclone rainfall, quantitative estimates for the anticipated rainfall increase must thus rely primarily on model projections.

20. The tropical cyclone seasons of 2004 and 2005 were highly unusual globally. Ten fully developed tropical cyclones made landfall in Japan in 2004, causing widespread damage. Southern China experienced much below-normal tropical cyclone landfalls and subsequently suffered a severe drought. Four major hurricanes caused extensive damage and disruption to Florida communities in 2004. In March 2004 southern Brazil suffered severe damage from a system that had hurricane characteristics, the first recorded cyclone of its type in the region. Five fully developed cyclones passed through the Cook Islands in a five week period in February-March 2005. The 2005 North Atlantic Hurricane Season broke several records including number of tropical cyclones, number of major hurricanes making landfall and number of category 5 hurricanes. In particular, the landfall of Hurricane Katrina at New Orleans and Mississippi caused unprecedented damage and more than 1300 deaths.

21. There is general agreement that no individual events in those years can be attributed directly to the recent warming of the global oceans. A more appropriate question is whether the probability of an event happening in a particular basin has been increased by the ocean warming, as for example the probability of cyclone development can change according to the phase of ENSO or of the Madden Julian Oscillation. It is well established that global atmospheric structure responds to the tropical sea surface temperature, and that such a response will affect the potential intensity (MPI) as well as other environmental factors such as vertical shear and relative vorticity. Thus it is possible that global warming may have affected the 2004-2005 group of events as a whole. The possibility that greenhouse gas induced global warming may have already caused a substantial increase in some tropical cyclone indices has been raised (e.g. Mann and Emanuel, 2006), but no consensus has been reached on this issue.

22. Tropical cyclones are characterized by large horizontal gradients of wind and pressure and their structure is difficult to measure and estimate. Satellite-based tropical cyclone structure estimates (past, present and future) are limited by both their sampling and instrument characteristics, and errors inherent to the technique used (Velden et al 2006, Demuth et al 2006, Bessho et al. 2006). Nonetheless, these techniques are used exclusively, with great success, to monitor tropical cyclone structure in most parts of the world. Even when aircraft-based reconnaissance is used to assess cyclone structure, operational procedures that are based upon understanding at the time can provide different estimates of the surface wind speed (Franklin et al. 2003, Knaff and Zehr 2006). The evolution of satellite-based techniques, satellite data capabilities and operational procedures have resulted in a far from ideal historical record of tropical cyclone maximum wind speeds (Landsea et al. 2006).

23. This community of international researchers and tropical cyclone forecasters believes that the public perception and response to cyclone forecasts are somewhat hampered by a lack of uniform forecast, monitoring and recording practices. Issues include different averaging periods for surface wind estimates, non-uniform operational gust factors, and multiple tables used to estimate maximum wind from satellite (e.g., the tables in Dvorak, 1975;1984 versus Koba 1990). These differences can result in a

confusing public message as well as non-uniform historical records that produce significantly different tropical cyclone climatologies (Kamahori et al. 2006).

24. Recent decades have seen a continuous increase in economic damage and disruption by tropical cyclones. This has been caused, to a large extent, by increasing coastal populations, by increasing insured values in coastal areas (e.g., Pielke 2005) and, perhaps, a rising sensitivity of modern societies to disruptions of infrastructure. For developing countries large loss of human life will continue as the increasing coastal populations are a result of population growth and social factors that are not easily countered (Zapata-Marti, 2006).

25. Projected rises in global sea level (IPCC 2001, Meehl et al., 2005) are a cause for concern in the context of society's vulnerability to tropical cyclone induced storm surges. In particular for the major cyclone disasters in history the primary cause of death has been salt-water flooding associated with storm surge.

26. A large body of research has been conducted on the potential impacts of climate change on tropical cyclones. This research has increased in volume over the past year in response to the recent research reports and in response to a number of recent high-impact tropical cyclone events around the globe. These include 10 landfalling tropical cyclones in Japan in 2004, five tropical cyclones affecting the Cook Islands in a five-week period in 2005, Cyclone Gafilo in Madagascar in 2004, Cyclone Larry in Australia in 2006, Typhoon Saomai in China in 2006, and the extremely active 2004 and 2005 Atlantic tropical cyclone seasons - including the catastrophic socio-economic impact of Hurricane Katrina. This recent international research is leading to major advances in understanding of the relationships between tropical cyclones and the large scale atmospheric state or "climate" as well as advances in the understanding of the observational record of tropical cyclones. Because of the rapid advances being made with this research, the findings in this statement may be soon superceded by new findings. It is recommended that a careful watch on the published literature be maintained.

27. Despite the diversity of research opinions on this issue it is agreed that if there has been a recent increase in tropical cyclone activity that is largely anthropogenic in origin, then humanity is faced with a substantial and unanticipated threat.

REFERENCES:

Bengtsson, L., K. Hodges, and E. Roeckner, 2006: Storm tracks and climate change. *J. Climate*, **19**, 3518-3543.

Bessho, K., M. DeMaria, J.A. Knaff, 2006: Tropical Cyclone Wind Retrievals from the Advanced Microwave Sounder Unit (AMSU): Application to Surface Wind Analysis. *J. of Applied Meteorology*. **45**:3, 399 - 415.

Chan, J.C.L., 1985: Tropical cyclone activity in the Northwest Pacific in relation to the El Nino/Southern Oscillation phenomenon. *Mon. Wea. Rev*., **113**, 599-606.

Chan, J. C. L., 2000: Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events. *J. Climate*, **13,** 2960-2972.

Chan, J.C.L., and K.S. Liu, 2004: Global Warming and Western North Pacific Typhoon Activity from an Observational Perspective. *J. Clim*., **17**, 4590-4602.

Chan, J.C.L., 2006: Comment on "changes in tropical cyclone number, duration and intensity in a warming environment, *Science*, **311**, p1713.

Chauvin, F., J.-F. Royer and M. Déqué, 2006: Response of hurricane-type vortices to global warming as simulated by ARPEGE-Climat at high resolution. *Clim. Dyn.*, **27**, 377-399.

Chia, H.-H., and C.F. Ropelewski, 2002: The interannual variability in the genesis location of tropical cyclones in the northwest Pacific. *J. Climate*, **15**, 2934-2944.

Chu., P.-S, 2005: ENSO and tropical cyclone activity, in Hurricanes and Typhoons: Past, Present, and Potential, edited by R.J. Murnane and K.B. Liu, pp297-332, Columbia University press, New York.

Demuth, J., M. DeMaria, and J.A. Knaff, 2006: Improvement of Advanced Microwave Sounding Unit Tropical Cyclone Intensity and Size Estimation Algorithms, *Journal of Applied Meteorology and Climatology*, **45**:11, 1573–1581.

Dvorak, V. F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**, 420-430

Dvorak, V.F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Technical Report NESDIS 11, 45pp.

Emanuel, K.A., 1987: The dependence of hurricane intensity on climate. Nature, 326, 483-485.

Emanuel, K.A., 1999: Thermodynamic contro; of hurricane intensity. *Nature*, **401**, 665-669.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature, **436***, 686-688.

Emanuel, K., C. DesAutels, C. Holloway and R. Korty, 2004: Environmental control of tropical cyclone intensity. *J. Atmos. Sci.,* **61**, 843-858

Franklin, J. L. , M.L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. *Wea. Forecasting*, **18**, 32-44.

Free, M., M. Bister and K. Emanuel, 2004: Potential intensity of tropical cyclones: Comparison of results from radiosonde and reanalysis data. J. Climate, 17, 1722-1727

Goldenberg, S. B., C. W. Landsea, A.M. Mesta-Nuñez, and W. M. Gray, 2001: The recent increase in Atlantic hurricane activity: causes and implications. *Science,* **293,** 474-479.

Gray, W.M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev*., **96**, 669-700.

Gray, W.M., 1975: Tropical cyclone genesis. Dept. of Atmospheric Science Paper No. 234, Colorado State University, Fort Collins, CO, 121 pp.

Gray, W.M., and J.D. Sheaffer, 1991: El Nino and QBO influences on tropical cyclone activity. In *Teleconnections linking worldwide climate anomalies*, edited by M.H. Glantz, R.W. Katz, and N. Nicholls, 257-284, Cambridge University Press, New York.

Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ. *J. Hydrometeorology* **5**, 64–85

Hasegawa, A. and S. Emori, 2005: Tropical cyclones and associated precipitation over the Western North Pacific: T106 atmospheric GCM simulation for present-day and doubled CO2 climates. *SOLA,* **1,** 145-148, SOI:10.2151/sola.2005-038

Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.-L., Webster, P., McGuffie, K. 1998: Tropical Cyclones and Global Climate Change: A Post-IPCC Assessment. *Bull. Amer. Meteor. Soc.*, ***79***, 19–38.

Ho, C.-H., J. –H. Kim, J. –H. Jeong, H. S. Kim, and D. Chen, 2006: Variations of tropical cyclone activity in the south Indian Ocean: ENSO and MJO effects. *J. Geophys. Res*. In Press.

Holland, G.J, 1993: Global Guide to Tropical Cyclone Forecasting. WMO, Geneva. _

Holland, G.J., 1997: The maximum potential intensity of tropical cyclones. *J. Atmos. Sci.,* **54**, 2519-2541.

International Ad Hoc Detection and Attribution Group (IADAG), 2005: Detecting and attributing external influences on the climate system: a review of recent advances. *J. Climate*, **18,** 1291-1314.

IPCC, 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Irwin, R.P., and R.E. Davis, 1999: The relationship between the Southern Oscillation Index and tropical cyclone tracks in the eastern North Pacific. *Geophys. Res. Lett*., **20**, 2251-2254.

Kamahori, H., N. Yamazaki, N. Mannoji, and K. Takahashi, 2006: Variability in intense tropical cyclone days in the western North Pacific. *SOLA*, **2**, 104-107, doi:10.2151/sola.2006-027.

Karoly, D.J., and Q.Wu, 2005: Detection of regional surface temperature trends. *J. Climate*, **18**, 4337-4343.

Klotzbach, P. J., 2006: Trends in global tropical cyclone activity over the past twenty years (1986-2005), *Geophys. Res. Lett*., **33**, L10805, DOI:10.1029/2006GL025881

Knaff, J. A., and R. M. Zehr, 2006: Reexamination of Tropical Cyclone Wind-Pressure Relationships, *Wea. Forecasting*, in press

Knutson, T.R. and R.E. Tuleya, 2004: Impact of CO_2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterization**.** *J. Climate .,* ***1****7*, 3477–3495.

Knutson, T.R., K. Emanuel, S. Emori, J. Evans, G. Holland, C. Landsea, K-b Liu, R. E. McDonald, D. Nolan, M. Sugi, Y. Wang. 2006a. Possible Relationships Between Climate Change and Tropical Cyclone Activity. Working Group Report 4.2. in Workshop Topic Reports, Sixth WMO International Workshop on Tropical Cyclones. Tropical Meteorology Research Programme Report Series. TMRP No. 72. WMO, Geneva.

Knutson, T.R., T.L. Delworth, K. W., Dixon, I. M. Held, J. Lu, V. Ramaswamy, D. Schwarzkopf, G. Stenchikov, and R.J. Stouffer, 2006. Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models. *J. Climate*, **19**(9), 1624-1651.

Koba, H., T. Hagiwara, S. Asano, and S. Akashi, 1990: Relationships between CI number from Dvorak's technique and minimum sea level pressure or maximum wind speed of tropical cyclone. *J. of Met. Research*, **42**, 59-67. (in Japanese)

Landsea, C.W., G.D. Bell, W.M. Gray, S.B. Goldenberg, 1998: The extremely active 1995 Atlantic hurricane season: environmental conditions and verification of seasonal forecasts. *Mon. Wea. Rev*., **126**, 1174-1193.

Landsea, C.W., R.A. Pielke, Jr., A.M. Mestas-Nuñez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change*, **42**, 82-129.

Landsea, C. W., C. Anderson, N. Charles, G. Clark, J. Dunion, J. Fernandez-Partagas, P. Hungerford, C. Neumann, and M. Zimmer, 2004: The Atlantic hurricane database re-analysis project: Documentation for the 1851-1910 alterations and additions to the HURDAT database. In: *Hurricanes and Typhoons: Past, Present and Future*, R. J. Murname and K.-B. Liu, Eds., Columbia University Press, p. 177-221.

Landsea, C. W., 2005: Hurricanes and global warming. *Nature,* **438,** doi:10.1038/nature04477.

Landsea,C.W., B.A.Harper, K.Hoarau, and J.A.Knaff, 2006: Can we detect trends in extreme tropical cyclones? *Science*. **313,** 452-454.

Mann, M. and K. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *EOS*, **87**, 233-241.

McBride, J.L., 1995: Tropical Cyclone Formation. Global perspectives on tropical cyclones, WMO/TD-No. 693, 289 pp.

McDonald, R.E., D.G. Bleaken, D.R. Creswell, V.D. Pope, and C.A. Senior, 2005: Tropical storms: representation and diagnosis in climate models and the impact of climate change. *Clim. Dyn*., **25**, 19-36.

Meehl G.A., W.M. Washington, W.D. Collins, J.M. Arblaster, A. Hu, L.E. Buja, W.G. Strand and H. Teng, 2005: How much more global warming and sea level rise? *Science*, **307**, 1769-1772.

Montgomery, M. T., M. M. Bell, S. D. Aberson, and M. L. Black, 2006: Hurricane Isabel (2003): New insights into the physics of intense storms. Part I: Mean vortex structure and maximum intensity estimates. *Bull. Amer. Met. Soc.*, **87**, 1335-1347.

Nicholls, N., 1979: Possible method for predicting seasonal tropical cyclone activity in the Australian region. *Mon. Wea. Rev*., **107**, 1221-1224.

Nicholls, N., 1984: Southern Oscillation, sea surface temperature, and interannual fluctuations in Australian tropical cyclone activity *J. Climatol*., **4**, 661-670.

Oouchi, K., J.Yoshimura, H. Yoshimura, R. Mizuta, S. Kusunoki, and A. Noda, 2006: Tropical cyclone climatology in a global-warming climate as simulated in a 20km-mesh global atmospheric model: frequency and wind intensity analysis. *J. Meteorol. Soc. Japan*, , **84**, 259-276.

Persing, J., and M. T. Montgomery, 2003: Hurricane superintensity. *J. Atmos. Sci.*, **60**, 2349-2371.

Pielke, R. A., Jr., 2005: Are there trends in hurricane destruction? *Nature,* **438,** E11

Raper, S., 1992: Observational data on the relationships between climatic change and the frequency and magnitude of severe tropical storms. In *Climate and Sea Level Change: Observations, projections and implications*, R.A. Warwick, E.M. Barrow, and T.M. L. Wigley (Eds) Cambridge University Press, 192-212.

Santer, B.D., T. M. L. Wigley, P. J. Gleckler, C. Bonfils, M. F. Wehner, K. AchutaRao, T. P. Barnett, J. S. Boyle, W. Brüggemann, M. Fiorino, N. Gillett, J. E. Hansen, P. D. Jones, S. A. Klein, G. A. Meehl, S. C. B. Raper, R. W. Reynolds, K. E. Taylor, and W. M. Washington, 2006: Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. *Proc. National Academ. Science*, **103**, 13905-13910.

Shapiro, L.J., and S.B. Goldenberg, 1998: Atlantic sea surface temperatures and tropical cyclone formation. *J. Atmos., Sci*., **11**, 578-590.

Shapiro, L., 1982: Hurricane climatic fluctuations. Part II: Relation to the large scale circulation. *Mon. Wea. Rev*., **110**, 1014-1040.

Sugi, M., A. Noda, and N.Sato, 2002: Influence of global warming on tropical cyclone climatology: an experiment with the JMA global model. *J. Meteorol. Soc. Japan*, **80**, 249-272.

Tonkin, H., G. Holland, C. Landsea, and S.Li, 1997: Tropical cyclones and climate change: A preliminary assessment. In *Assessing Climate Change: Results from the Model Evaluation and Consortium for Climate Assessments*, W. Howe and A. Henderson Sellers, eds., Taylor and Francis Group, plc., London, 327-360.

Tonkin, H., G.J. Holland, N. Holbrook, A.Henderson-Sellers, 2000: An evaluation of thermodynamic estimates of climatological maximum potential tropical cyclone intensity. *Mon. Wea. Rev*., **128**, 746-762

Tropical Meteorology Research Program (TMRP), 2006: Statement on Tropical Cyclones and Climate Change. Available at http://www.bom.gov.au/bmrc/clfor/cfstaff/jmb/CAS-statement.pdf

Velden, C., B. Harper, F. Wells, J. L. Beven II, R. Zehr, T. Olander, M. Mayfield, C. Guard, M. Lander, R. Edson, L. Avila, A. Burton, M. Turk, A. Kikuchi, A. Christian, P. Caroff, and P. McCrone, 2006: The Dvorak Tropical Cyclone Intensity Estimation Technique: A Satellite-Based Method that Has Endured for over 30 Years. *Bull. Amer. Meteor. Soc.*, **87**, 1195-1210.

Walsh, K. J. E., K.-C. Nguyen, and J. L. McGregor, 2004: Fine-resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia. *Clim. Dyn.,* **22,** 47-56, DOI: 10.1007/s00382-003-0362-0

Wang, B. and J. C. L. Chan, 2002: How ENSO regulates tropical storm activity over the western North Pacific. *J. Climate*, **15,** 1643-1658.

Webster, P.J., G.J. Holland, J.A. Curry, and H-R. Chang, 2005: Changes in tropical cyclone number, duration and intensity in a warming environment. *Science, **309***, 1844-1846.

WMO., 2006. Workshop Topic Reports, Sixth WMO International Workshop on Tropical Cyclones. Tropical Meteorology Research Programme Report Series. TMRP No. 72. WMO, Geneva.

Yoshimura, J., M. Sugi and A. Noda, 2006: Influence of greenhouse warming on tropical cyclone frequency. *J. Meteor. Soc. Japan*, **84**, 405-428.

Zapata-Marti, R., 2006. Disaster's impact: Understanding and attributing trends and projections of damage and losses. The ECLAC perspective, White paper prepared for Workshop on Climate Change and Disaster Losses: Understanding and Attributing Trends and Projections, UNITED NATIONS - Economic Commission for Latin America and the Caribbean (ECLAC).