Low frequency variability of tropical cyclone potential intensity 2. Climatology for 1982–1995

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[1] In this note, we describe the method of calculating a climatology of tropical cyclone potential intensities for the years 1982–1995, as displayed at http://www.mit.edu/~emanuel/pcmin/climo.html. The climatology has been constructed from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis and the Reynolds' Global Sea Surface Optimum Interpolation (OI) temperature analysis. We estimate errors in potential intensities resulting from known problems in the data and discuss the results. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); *KEYWORDS:* Tropical cyclones, potential intensity, reanalysis, climatology

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1. Introduction and Data

[2] Thermodynamic methods of obtaining potential intensities [*Emanuel*, 1986 and *Holland*, 1997] have considerable skill in estimating observed maximum intensities [*Tonkin et al.*, 2000]. Even though most storms do not achieve their potential intensity owing to adverse effects of the ocean feedback [*Schade and Emanuel*, 1999] and the vertical wind shear in the atmosphere (for other possible effects, see *Emanuel* [2000]), the relevance of potential intensity, however, is not restricted to estimation of maximum intensities. *Emanuel* [2000] calculated cumulative distribution functions (CDFs) of tropical cyclone wind speeds normalized by climatological potential intensity, the calculation of which is described in M. Bister and K. A. Emanuel (Low frequency variability of tropical cyclone potential intensity, Part I, Interannual to interdecadal variability, manuscript submitted to *Journal of Geophysical Research*, 2002). The CDFs of storms whose lifetime maximum exceeded 32 m s^{-1} and which were not limited by declining potential intensity were observed to be nearly linear. This implies that there is an equal likelihood that any given hurricane-strength tropical cyclone will achieve any given intensity up to its potential intensity. There is also a uniform probability that a storm that has not achieved its lifetime maximum intensity will have an intensity that is any given fraction of its lifetime maximum intensity. These results suggest that any climatic change in potential intensity would affect the intensity distribution of real tropical cyclones uniformly if the linear functions are truly universal.

[3] We use the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis [*Kalnay et al.*, 1996 and *Kistler et al.*, 2001] and the Reynolds' Global Sea Surface Optimum Interpolation (OI) temperature analysis [*Reynolds and Smith*, 1994] to calculate a climatology of potential intensities for years 1982–1995. In the rest of this section, we give a short description of the data and estimate the effect of known data problems on the calculated potential intensities.

[4] In situ and satellite SSTs are used in the OI weekly SST analysis. The satellite data are adjusted for biases using the method of *Reynolds* [1988] and *Reynolds and Marsico* [1993]. The bias correction, however, adds a small amount of noise in time. Therefore binomial filter of 1/4 – 1/2 – 1/4 was used in time with a time step of a week as recommended by Reynolds (in http://dss.ucar.edu/datasets/ds277.0/data/oi/wkly/oiweek.info).

[5] The NCEP/NCAR Reanalysis (hereinafter referred to as Reanalysis) provides a data set that is free of those false trends that arise from changes in the assimilation system. During years 1982–95, data assimilated in the Reanalysis have been plentiful [e.g., *Kistler and Kalnay*, 2000]. Satellite data have been assimilated in the Reanalysis for this whole time period. Also, the SST analysis used in the Reanalysis has been the same for the whole time period, and we use the same SST analysis here to obtain the potential intensity climatology. As noted by *Onogi* [2000], the quality of the radiosonde observing system has been

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significantly better after the 1970s than before the 1960s. These facts suggest that the Reanalysis data from 1982–95 may be at its best. *Santer et al.* [1999] calculated root mean square (RMS) differences between the gridded sounding data set compiled by *Parker et al.* [1997] at the Hadley Centre for Climate Prediction and Research (HadRT1.1) and the Reanalysis data. Depending on the method, the global RMS difference of seasonal mean anomalies of temperature in a layer around 74 hPa was as small as 0.13 or 0.26 C.

[6] However, spurious warming of the stratosphere and upper troposphere associated with the use of satellite data has plagued the Reanalysis since 1977–79. Note that its effect does not show up in *Santer et al.*'s RMS differences due to their particular choice of the reference period. Studies concerning the spurious warming have been reviewed by Bister and Emanuel (submitted manuscript, 2002). They estimated the spurious warming to have decreased the global mean potential intensity by about 2 m s^{-1}. As the spurious increase of temperature in the Reanalysis has not occurred uniformly in space, the spatial variation of the calculated potential intensity is also contaminated. To crudely estimate the maximum error in the calculated potential intensities, we note that the mean temperature between latitudes 27°S and 27°N close to the tropopause seems to have increased by about 2–3 K around 1979 (see Figure 4 in Bister and Emanuel, submitted manuscript, 2002). Over the equatorial mid-Pacific, the increase reaches its maximum value of 4–5 K (Bister and Emanuel, submitted manuscript, 2002). A crude adjustment for the spurious temperature increase was applied to the potential intensity calculation by comparing years with similar tropical SST before and after 1979. The adjustment was shown to increase the global mean PI by about 2 m s^{-1}. Therefore, over the equatorial mid-Pacific, the corresponding correction would probably yield about 4 m s^{-1} higher potential intensities. In summary, local errors in potential intensities owing to the spurious temperature increase can be up to 4 m s^{-1}.

[7] *Anderson et al.* [1991] and *Kelly et al.* [1991] showed that the retrieval methods used by National Environmental Satellite, Data and Information Service (NESDIS) before and after 1988 have had large problems over the Kuroshio and the Gulf Stream. The biases are shown for the lower to mid-troposphere. If similar biases exist for the upper troposphere and tropopause, then potential intensities are contaminated since they are very sensitive to temperature close to 100 hPa [Bister and Emanuel, submitted manuscript, 2002]. Local errors in Reanalysis temperatures can also be caused by problems with the sounding data. A particularly large error correction was needed for the data from radiosonde stations in Australia and New Zealand, which resulted in reducing the stratospheric cooling by 3 C over 1979–96 [*Parker et al.*, 1997]. However, a similar bias correction has not been made in the radiosonde data assimilated by NCEP [*Santer et al.*, 1999].

[8] In addition to the spurious temperature increase around 1979, Reanalysis temperatures have experienced spurious cooling starting in 1991-2 [*Basist and Chelliah*, 1997 and *Hurrell and Trenberth*, 1998]. It has been suggested that a change in NESDIS retrieval methods in 1992 has contributed to this cooling. According to *Basist and Chelliah*, the cold trend seemed to start reversing in 1995. In Bister and Emanuel, (submitted manuscript, 2002), it was estimated that the spurious cooling, if it also exists in the upper troposphere, could lead to an overestimate of potential intensity of about 0.3 m s^{-1}. This spurious cooling may be related to the Reanalysis temperatures of the tropical tropopause being warmest compared to the radiosonde temperatures in 1989–1993 [*Randel et al.*, 2000].

[9] The SST analysis has also been noted to show cooling with respect to the Global Sea Ice and Sea Surface Temperatures (GISST) analysis from the U. K. Meteorological Office [*Hurrell and Trenberth*, 1999]. The OI data may be getting too cold because of problems with incompletely corrected satellite data (see *Hurrell and Trenberth* [1999] and references therein). Such an error would lead to an underestimation of potential intensity. If this error is on the order of 0.1 C as suggested by Figure 7 of *Hurrell and Trenberth* [1999], its effect is likely to be of the same order of magnitude as the effect of the spurious cooling in the Reanalysis temperatures (Bister and Emanuel, submitted manuscript, 2002).

[10] The net effect of the errors is hard to estimate because the magnitude, vertical extent, geographical distribution, and temporal variation of many errors are unknown. Moreover, radiosonde data are likely to contain additional biases that have large spatial and temporal variation [*Gaffen et al.*, 2000]. Their net effect is to be determined in the future.

[11] Improvements in the current potential intensity climatology are likely with the new NCEP Reanalysis scheduled for 2005 or so (Proceedings of the Second WCRP International Conference on Reanalyses 2000, Conference summary, p. xi, WCRP-109, WMO/TD-NO.985). In the new Reanalysis, satellite radiances will be assimilated directly, which will circumvent problems with changes in the NESDIS retrieval algorithms and which will hopefully alleviate the warm bias of the current Reanalysis in the upper troposphere and stratosphere. Also, any possible improvements in the correction of satellite data which is used in the OI SST data set are likely to lead to improvements in the calculated potential intensities.

2. Results

[12] The technique represents an implementation of that presented in *Emanuel* [1995] to the case of an irreversible heat engine. The description presented by *Emanuel* [1995] has been further modified to account for dissipative heating, which had been neglected in earlier treatments. These modifications are described in *Bister and Emanuel* [1998]. The modified method of calculating potential intensity is described in (Bister and Emanuel, submitted manuscript, 2002). We here note only that the input to the scheme at each grid point is the sea surface temperature and vertical profiles of pressure, temperature, and mixing ratio from the Reanalysis data. The raw maximum wind speed estimates are reduced by 10% as a crude means to reduce the gradient wind speeds to wind speeds at the altitude of 10 m.

[13] The NCEP Reanalysis daily average data set has a resolution of 2.5° × 2.5° and the NCEP OI weekly SST analysis has a resolution of 1° × 1°. Potential intensity is calculated for each atmospheric data grid point. The SST of the closest ocean data grid point is used in the calculation of PI. If the closest ocean data grid point is not over ocean but land, then potential intensity is not calculated. But if the

ocean data grid point is over ocean, then the routine calculates potential intensity even if the corresponding atmospheric data grid point was located over land.

[14] Potential intensities were calculated for each day for years 1982–1995. Both maximum velocity and minimum pressure were calculated. The resulting daily values were used to calculate the following statistics about the PI data:

1. Monthly mean minimum central pressures and maximum surface wind speeds to show how the potential intensity depends on the season.
2. Standard deviation from monthly mean minimum central pressures and maximum surface wind speeds.
3. 90th percentile minimum central pressure and maximum surface wind speed. I.e., 10% of the individual daily mean values in the given month represent greater intensity than this number. These maps thus show the strongest potential intensities during any month.
4. Lowest value of 90th percentile minimum surface pressure and highest value of the 90th percentile maximum surface wind speed within 1000 km of each point. These maps are provided to show the potential threat from hurricanes that move fast over a region with a strong gradient of potential intensity and which therefore may have larger intensities than the local potential intensity.
5. Lowest monthly mean minimum central pressure and highest monthly mean maximum surface wind speed in each year. These maps show the interannual variation of the potential intensity of hurricanes during the 14 years of analysis.
6. Lowest monthly 90th percentile minimum central pressure and highest monthly 90th percentile maximum surface wind speed in each year.

[15] The last two annual statistics give values for the "worst" month and the worst month is allowed to depend on the grid point, i.e., different grid points may show values for different months. These statistics can be obtained from http://www.mit.edu/~emanuel/pcmin/climo.html. We stress that PI is only achieved by a small fraction of all tropical storms and in some regions PI may never be achieved due to, e.g., cold ocean currents upstream [*Emanuel*, 2000].

[16] In the following, we discuss some interesting features of potential intensity which can be seen in maps showing the maximum surface wind speed. Generally, the strongest monthly mean PIs occur in a band from east of Somalia to the Date Line. The strongest monthly mean values of PI occur in April. In April, the monthly mean PI is strongest to the southwest of India and in November to the west of the Date Line. The values exceed 100 m s^{-1} to the southwest of the Indian peninsula. In the Atlantic, the largest values of PI occur in September and October.

[17] The monthly mean values of PI exceed 32 m s^{-1} over the South Atlantic and far to the east of the Date Line. Both regions are void of hurricanes in reality. Over the South Atlantic, the vertical wind shear may be large enough to prevent the formation of tropical cyclones. *Gray* [1968] has suggested that the lack of an Intertropical Convergence Zone in this region can prevent formation of hurricanes. The smallness of the Coriolis parameter within a few degrees from the Equator prevents formation of tropical cyclones there. This is not accounted for in the potential intensity theory and the maps do show large potential intensities right at the Equator.

[18] The standard deviation of the PI is largest in the subtropics of both hemispheres. Perhaps the reason is that in the subtropics the SST has a smaller direct influence on the overlying atmosphere than at lower latitudes. Also over and near the Gulf Stream, the standard deviation of PI is quite large.

[19] Maps of highest monthly mean of maximum surface wind speed in each year show anomalously low values of PI over the West Pacific and anomalously large values of PI east of the Date Line in 1983, a year of strong El Niño. The band, extending form east of Somalia to the Western Pacific shows large PIs in 1986 and in 1991–1995. The largest area with PIs exceeding 100 m s^{-1} was achieved in 1994. PI exceeded 90 m s^{-1} over the Gulf of Mexico and the Caribbean Sea in an exceptionally large area in years 1987, 1990, and 1995.

[20] Comparing the highest monthly 90th percentile maximum surface wind speed to the monthly mean values shows that the former are about 10% larger than the latter.

[21] For some particular cities and regions, the smallest 90th percentile minimum central pressure and the largest 90th percentile maximum central wind speed from the 12 months are provided in the form of a table. It should be noted that both the Persian Gulf and the Red Sea are only a couple of hundred kilometers wide. Therefore, only a midget tropical cyclone could be possible over these regions. A larger hurricane would be adversely affected by the land area beneath it.

[22] The authors stress that caution should be used in interpreting PIs representing the extrema within 1000 km of each point. It should be noted that there are few regions where hurricanes can be expected to move rapidly enough to sustain intensities well in excess of the local potential intensity. Also, these values can be strongly affected by anomalous point values of PI. Especially, the value for San Diego is unrealistic since a hurricane would be very unlikely to move fast enough in this region so that its intensity would not decrease significantly while it approaches San Diego.

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