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How strong are the Southern Hemisphere storm tracks?

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[1] The real strength of the Southern Hemisphere (SH) storm tracks is poorly known, as the NCEP-NCAR and ECMWF reanalyses differ significantly in this measure. In this work, the COSMIC GPS radio occultation dataset is used to investigate this issue. The ratio of the strength of the SH storm tracks to that in the Northern Hemisphere (NH) based on the COSMIC dataset can be regarded as close to the true inter-hemisphere ratio since the dataset has similar biases and errors in both hemispheres. Comparing this ratio with that based on the reanalysis, it is found that the strength of the SH storm tracks in the NCEP-NCAR reanalysis is significantly biased low by at least 25% at 300 hPa, while those in the ECMWF reanalyses are much closer to that inferred from COSMIC observations but ERA40 may be biased low by 5–10%. **Citation:** Guo, Y., E. K. M. Chang, and S. S. Leroy (2009), How strong are the Southern Hemisphere storm tracks?, *Geophys. Res. Lett.*, *36*, L22806, doi:10.1029/2009GL040733.

1. Introduction

[2] One may be surprised that to this day and age, one of the fundamental properties of the atmospheric general circulation – the real strength of the Southern Hemisphere (SH) storm tracks – is still not clear. When one computes storm track activity measures (to be defined below) from the NCEP-NCAR and ECMWF reanalyses, the most widely used atmospheric data sets, these measures differ significantly. For example, *Chang* [2000] found that the amplitudes of eddy meridional wind variance computed from ECMWF ERA15 are about 40% larger than those from the NCEP-NCAR reanalysis in the SH. *Dell'Aquila et al.* [2007] also found that SH transient eddy statistics computed from ERA40 data are generally characterized by larger variances than those computed from the NCEP-NCAR reanalysis, especially in the high frequency spectral region.

[3] The significant differences between the two reanalyses regarding this issue are mainly due to the lack of in situ conventional observations over the SH storm track regions, which are located mostly over the oceans. In the Northern Hemisphere (NH), even though the storm track peaks are also located over the oceans, there are large numbers of commercial aircraft and surface ship observations to constrain the analyses, and NH storm track activity is quite consistent between the two reanalyses [e.g., see *Chang*, 2007, Figure 2]. Even after the advent of massive satellite data in the late 1970s, the discrepancy between the two reanalyses in depicting the strength of the SH storm tracks has not decreased but instead has increased. *Guo and Chang* [2008] found that this is most likely due to the different ways the two reanalyses assimilate the satellite data. The NCEP-NCAR reanalysis assimilates retrieved satellite temperature, while the ECMWF reanalysis assimilates raw satellite radiance. *Guo and Chang* [2008] found that the retrieved satellite temperature variance is biased low, resulting in weaker baroclinic wave activity, hence weaker storm tracks in the SH in the NCEP-NCAR reanalysis. However, it is not known whether SH storm track activity in ERA40 is biased or not.

[4] In this paper, the strength of the SH storm tracks is examined quantitatively for the first time due to the availability of a new independent dataset: GPS radio occultation obtained by the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC). The advantages of the COSMIC GPS occultation dataset and the method of applying it to investigate the strength of SH storm tracks are presented in section 2. Results and discussions are presented in sections 3 and 4, respectively.

2. Data and Methodology

[5] The COSMIC project [*Anthes et al.*, 2008] was implemented in April, 2006. For more information, see http://www.cosmic.ucar.edu/index.html. With minimal constraints on humidity, temperature and geopotential height as a function of pressure can be deduced from the mid troposphere through much of the stratosphere, with a precision of ∼0.5 K and ∼15 m near the tropopause [*Kursinski et al.*, 1997; *Kuo et al.*, 2004]. Since radio occultation cannot uniquely distinguish between water vapor and the "dry" atmosphere in the lower troposphere, information on pressure and water vapor is ambiguous. In this study, geopotential heights at 300 hPa are used. Since our focus is on the mid-latitudes upper troposphere and lower stratosphere, impacts of water vapor are negligible [*Kursinski et al.*, 1995]. Compared with other observational data, the COSMIC GPS radio occultation data have several distinct advantages that suit our purpose very well. 1) It provides about 2000 soundings per day globally, which is sufficient to resolve the mid-latitude baroclinic waves. 2) The soundings have similar distribution, biases and errors in both hemispheres, although latitudinal distribution is not uniform (more soundings in higher latitudes). 3) This dataset has not been assimilated into either the NCEP-NCAR or the ERA40 reanalyses, thus can serve as an independent data source to validate the reanalyses.

[6] The daily COSMIC geopotential heights at a constant pressure level are first mapped onto a 2.5° by 2.5° lon-lat grid using the Bayesian interpolation algorithm with a spherical

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harmonic basis [*Leroy*, 1997]. Bayesian interpolation permits mapping of irregularly distributed data with unknown error characteristics and does so in a way that prevents over-fitting [*MacKay*, 1992; *Leroy*, 1997]. When conducting the Bayesian interpolation, the order of the spherical harmonic basis is chosen to be 30, a 961-coefficient fit which requires at least that number of independent data. (The number of independent terms in a spherical harmonic fit is the square of the sum of the order of the fit and 1.) An order 30 spherical harmonic expansion is approximately equivalent to 6° resolution in the mid-latitudes. This resolution is chosen to be high enough to resolve the spatial scales of baroclinic wave activity and low enough to resolve the temporal scales of baroclinic wave activity under the constraint that COSMIC obtains ~2000 soundings per day. A higher order fit would require more independent data and thus a longer time interval of COSMIC data, in which case more spatial structure would be resolved but at the expense of washing out temporal structure. Since storm track activity depicts a strong seasonal cycle, two full years of data (January 2007 to December 2008) have been analyzed. Within this period, for 300 hPa there were 32 days when the number of COSMIC observations is insufficient for the analysis to be carried out. The daily geopotential height map obtained by this scheme can reproduce most of the large scale wave features depicted in the reanalysis. For example, Figures 1a and 1b show the great qualitative similarity between the interpolated COSMIC geopotential height at 300 hPa and the NCEP-NCAR reanalysis on a randomly chosen day, January 1, 2008 in this case. Overall, the RMS difference of daily averaged 300 hPa geopotential height between our COSMIC Bayesian analysis and NCEP-NCAR reanalysis data (which were smoothed to T30 resolution for direct comparison with the COSMIC analysis) is about 25 m when averaged over the NH. We have also interpolated COSMIC data using another more commonly used interpolation scheme, the Cressman objective analysis [*Cressman*, 1959]. The results (not shown here) show no substantial difference with those based on the Bayesian scheme, which suggests our results are not sensitive to the interpolation scheme used.

[7] To depict storm track activity, various eddy variance and covariance statistics, including variance in mean sea level pressure, geopotential height, and meridional wind perturbations, as well as poleward eddy momentum and heat fluxes, have been used [e.g., *Chang et al.*, 2002]. In this study, variance in 300 hPa geopotential height perturbations (z') is used to depict storm track activity. z' is chosen because it can be directly retrieved based on COSMIC observations. This measure (as well as several other storm track measures such as meridional wind variance and poleward eddy momentum flux) peaks at 300 hPa, close to the mid-latitude tropopause level. To focus on baroclinic wave activity and filter out low frequency variability, a 24-hour difference filter [*Wallace et al.*, 1988] has been employed. Thus, geopotential height perturbation (z') is defined as

$$z'(t) = z(t + 24\,\mathrm{hr}) - z(t), \qquad (1)$$

while storm track activity (ZZ) is defined as

$$ZZ = \overline{z'^2} = \overline{[z(t + 24\,\mathrm{hr}) - z(t)]^2}. \qquad (2)$$

The overbar in equation (2) represents time average, usually over a month. As discussed in previous studies, this filter has half power points at 1.2 and 6 days [see *Wallace et al.*, 1988, Figure 2], and month-to-month variability in the variance computed based on this filter is very similar to those computed with other commonly used band-pass filters [see *Chang and Fu*, 2002, Appendix B].

[8] NCEP-NCAR, ERA15, and ERA40 reanalyses pressure level data, also on a 2.5° × 2.5° lon-lat grid, as well as ERA-Interim data on a 1.5° × 1.5° grid, have been analyzed to compare with the COSMIC analyses. Note that unlike NCEP-NCAR reanalysis, ERA-Interim assimilates GPS occultation data from COSMIC, CHAMP, and GRACE [*Healy*, 2008], hence cannot be considered to be independent from COSMIC data. For the reanalyses, daily geopotential height is first calculated by averaging the 6-hourly data. For direct comparisons with the COSMIC Bayesian analysis, the reanalysis data are also smoothed to a resolution of T30. In this study, NCEP-NCAR reanalysis data from 1979 to 2008 are used. ERA15 data are only available between 1979 and 1993, while ERA40 data are available up to 2002. ERA-Interim data are available from 1989 to 2008. Since the ECMWF ERA15 and ERA40 reanalyses do not overlap with COSMIC data, we will first compare COSMIC data with NCEP-NCAR and ERA-Interim data for January 2007 to December 2008, and then compare the different reanalyses prior to that period. For reference, the spatial distributions of ZZ at 300 hPa, averaged over the 2 years, computed based on COSMIC Bayesian analysis and the NCEP-NCAR reanalysis, are shown in Figures 1c and 1d. The spatial patterns are very similar, but the magnitude of ZZ in the SH is significantly greater in the COSMIC analysis.

[9] Since the COSMIC data have similar spatial distribution as well as errors and biases in the two hemispheres, it is reasonable to assume that the inter-hemispheric ratio in storm track activity computed from the COSMIC data should be robust. We take the inter-hemisphere ratio based on the COSMIC data and compare it with the ratios based on the reanalyses. In this way, the biases in the reanalyses in the SH, and thus the real strength of the SH storm tracks, can be inferred under the assumption that the reanalyses are much more reliable for the NH than for the SH.

3. Results

[10] The zonal mean of the 24-hour difference filtered variance of 300 hPa geopotential height (ZZ) averaged from January, 2007, to December, 2008, is shown in Figure 2a. The zonal means have been multiplied by cosine of latitude to show their contributions to the hemispheric mean. The three curves are from the NCEP-NCAR reanalysis, the ERA-Interim reanalysis, and the Bayesian interpolation of COSMIC data (at a resolution of T30), respectively. In Table 1, the ratios of the SH to the NH averaged baroclinic wave activity computed from the different datasets are shown. Here, hemispheric average refers to averaging from 20° to 70° latitude. For the Bayesian interpolation, we have

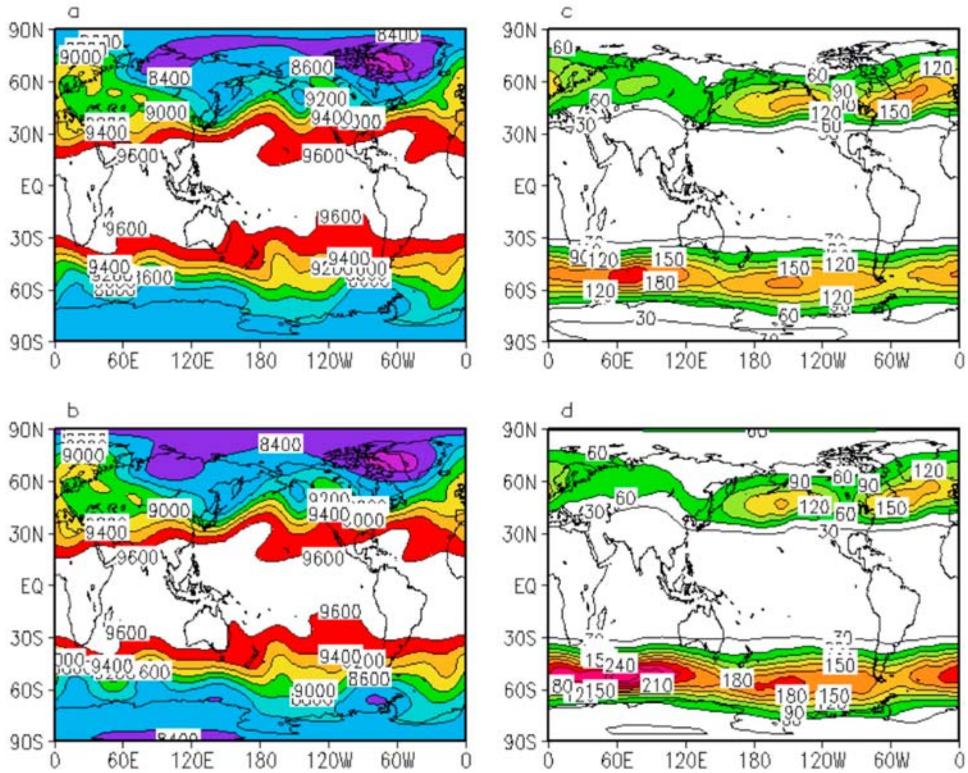

Figure 1. (a) Daily geopotential height at 300 hPa on Jan 1, 2008 for the NCEP-NCAR reanalysis. (b) Same as Figure 1a but for the gridded COSMIC dataset by the Bayesian interpolation scheme. Units: m. (c) The 24-hour difference variance of 300 hPa geopotential height for the NCEP-NCAR reanalysis from Jan 2007–Dec 2008. (d) Same as Figure 1c but for the COSMIC dataset. Units: 100 m^2.

tested the sensitivity to the resolution by truncating the analysis at resolutions ranging from T25 to T35. The inter-hemispheric ratio (listed in Table 1) is nearly unaffected by the choice of resolution. The ratio deduced from COSMIC data is slightly over 1.8.

[11] Figure 2a shows that the baroclinic waves in the NCEP-NCAR and ERA-Interim reanalyses have similar strengths in the NH and are slightly stronger than those in the COSMIC data. However, they are significantly different in the SH with much weaker strength in the NCEP-NCAR reanalysis, and with ERA-Interim indistinguishable from the COSMIC data. The NCEP-NCAR reanalysis presents slightly stronger NH storm tracks but much weaker SH storm tracks than the COSMIC data, which suggests the amplitude of the SH storm tracks are biased low in it. When averaged over the two years, the SH/NH ratio of ZZ computed based on the NCEP-NCAR reanalysis data is 1.37, about 25% smaller than the ratio computed based on the COSMIC data. The ratio computed based on the ERA-Interim reanalysis is 1.72, only slightly smaller than that computed based on COSMIC data. The consistency between ERA-Interim reanalysis and COSMIC data should be expected, since ERA-Interim assimilates COSMIC data during this period.

[12] The month-to-month ratios between the SH and the NH averaged baroclinic wave activity (ZZ) during January

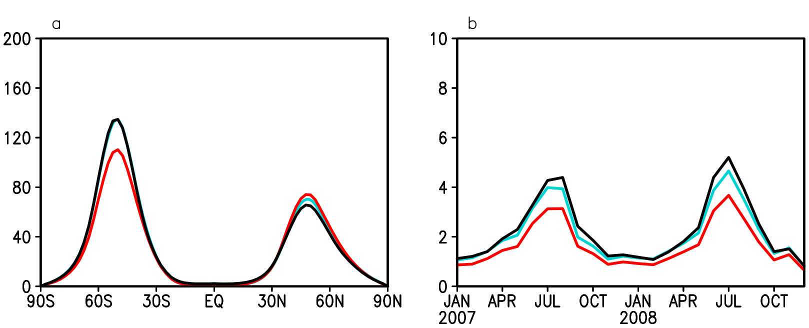

Figure 2. (a) The zonal mean of the 24-hour difference variance of geopotential height (ZZ) at 300 hPa, multiplied by cosine of the latitude, averaged during Jan 2007–Dec 2008 for the NCEP-NCAR reanalysis (red), the ERA-Interim reanalysis (cyan), and the COSMIC dataset interpolated by the Bayesian scheme (black). Units: 100 m^2. (b) The month-to-month inter-hemisphere (SH to NH) ratio of ZZ from Jan 2007–Dec 2008 for these 3 datasets.

Table 1. The Inter-hemisphere (SH to NH) Ratios of the 24-Hour Difference Variance of Geopotential Height at 300 hPa for Different Datasets

Dataset	NCEP Rean	ERA-Interim	COSMIC Bayesian		
			T25	T30	T35
2007–2008	1.37	1.72	1.81	1.82	1.84

2007 to December 2008 are shown in Figure 2b. The annual cycle is clearly seen, with the ratio significantly larger than 1 during boreal summer since the NH storm tracks are weakest during that period due to small equator-to-pole temperature gradient during that season. During the boreal winter, the ratio is smaller but still close to 1, since even though the temperature gradient in the NH is larger than that in the SH at that time, the strong stationary waves in the NH winter implies weaker storm track amplitudes [e.g., *Nakamura et al.*, 2002]. All three curves vary consistently with time although the magnitudes of the ratio are different. The NCEP-NCAR reanalysis shows the smallest ratio, while the COSMIC data show largest ratios. Based on Figure 2b, it is clear that the low bias of the SH storm track in the NCEP-NCAR reanalysis occurs throughout the year.

[13] While a direct comparison of NCEP and COSMIC data suffices to estimate biases in NCEP storm track strengths, one must resort to a comparison between ERA40 data and NCEP-NCAR reanalysis data to infer biases in ERA40 storm track strengths because ERA40 terminated in August, 2002. The variances of 24-hour difference of daily geopotential height at 300 hPa (ZZ) are computed for all four reanalyses datasets during the time when they are available. The zonal means averaged during 1989–2001 for NCEP-NCAR, ERA40, and ERA-Interim reanalyses are shown in Figure 3a. The amplitudes of the baroclinic waves in the three reanalyses are nearly the same in the NH but show significant differences in the SH, with amplitude in the ERA40 much stronger than that in the NCEP-NCAR reanalysis, which is consistent with the results of *Guo and Chang* [2008]. The amplitude in the ERA-Interim is even stronger than that in the ERA40.

[14] The ratio between SH and NH ZZ, when ZZ is averaged over a 24-month (or 2-year) running mean, is shown in Figure 3b for all 4 reanalyses. Here, a 2-year running mean is computed so that results can be compared with the 2-year mean computed for the 2007–2008 period discussed above. The ratio for NCEP-NCAR reanalysis is shown from 1979 through 2008, while results for the ECMWF reanalyses are only available over parts of the period. The ratio computed from ERA40 shows some inter-annual variability and varies between a value of 1.5 and 1.7. Meanwhile, the ratio computed based on NCEP-NCAR reanalysis data displays not only interannual variability, but also a trend. The trend in the NCEP-NCAR reanalysis data is mainly due to a steady increase in ZZ in the SH, while for ERA40, such an increasing trend in SH ZZ is not found (not shown).

[15] It is not clear whether the trend exhibited by the NCEP-NCAR reanalysis data is real or not. We are analyzing various diagnostic fields (such as energetics, clouds, and radiation) produced by the reanalysis projects to examine how internally consistent their respective trends (or absence of trends) in ZZ are with those in the diagnostic fields. Nevertheless, if ERA40 is correct and there is no trend, Figure 3b suggests that SH storm track activity in the ERA40 may be biased low by 5–10%, since the SH/NH ratio computed based on ERA40 never exceeds 1.7 between 1979 and 2002, while the ratio computed from COSMIC is over 1.8. On the other hand, if the NCEP-NCAR reanalysis is correct and there is a trend, the average value of the ratio computed based on the NCEP-NCAR reanalysis during the last 5 years of the ERA40 period (1997–2001) is 1.32, while the ratio for 2007–2008 is 1.37 and is only slightly larger. The average value of the ratio between 1997 and 2001 computed from ERA40 data is 1.64. Thus even if the ratio in ERA40 increases as exhibited in the NCEP-NCAR reanalysis data, the ERA40 ratio for 2007–2008 is likely to be near 1.69, which is still more than 5% smaller than the ratio computed based on COSMIC data. Thus the SH storm track activity in the ERA40 data is also likely biased weak, albeit the bias is significantly less than that for the NCEP-NCAR reanalysis data.

[16] During the period that they overlap (1989–2002), the ratio computed based on ERA-Interim is consistently higher than that based on ERA40. Given our conclusion that ERA40 might be biased low, this suggests that ERA-Interim reanalysis should represent an improvement over ERA40. However, it is interesting to note that during most of 1979–1993, the ratio computed based on ERA15 is also higher than that based on ERA40 (Figure 3b). In particular, during 1989–1993, when all 3 datasets are available, the ratio

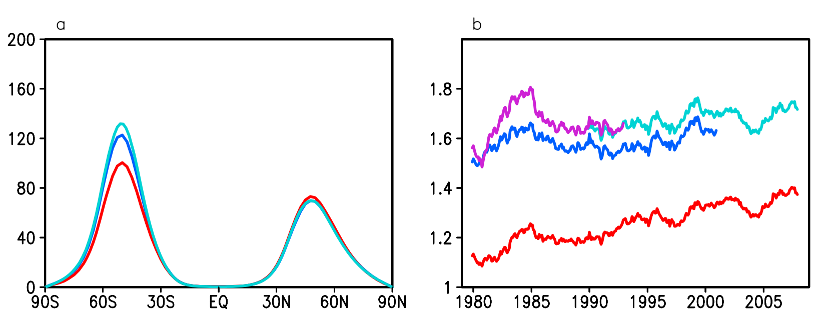

Figure 3. (a) The zonal mean of the 24-hour difference variance of geopotential height (ZZ) at 300 hPa, multiplied by cosine of the latitude, averaged during Jan 1989–Dec 2001 for the NCEP-NCAR reanalysis (red), the ERA40 (blue), and the ERA-Interim (cyan). Units: 100 m^2. (b) The 2-year running mean of the inter-hemisphere ratio (SH to NH) of 300 hPa ZZ for the NCEP-NCAR reanalysis (red), the ERA15 (purple), the ERA40 (blue), and the ERA-Interim (cyan).

computed based on ERA15 and ERA-Interim are nearly the same, and both are larger than that based on ERA40. The reason why ERA15 and ERA-Interim agree better with COSMIC data than ERA40 is unknown, but this suggests that improvements in model and data assimilation do not necessarily lead to a monotonic improvement in the analysis product.

4. Conclusions and Discussions

[17] The real strength of the SH storm tracks is investigated using the recently available COSMIC GPS radio occultation dataset, from which geopotential height can be directly retrieved as a function of pressure. The COSMIC mission provides about 2000 profiles daily, globally distributed, which is dense enough to resolve the mid-latitude baroclinic waves. The COSMIC dataset produces a reliable inter-hemisphere ratio of storm tracks strengths since its biases and errors are similar in both hemispheres. Furthermore, it is not assimilated in the NCEP-NCAR and ERA40 reanalyses and thus can be treated as an independent data source to validate the reanalyses. Comparing the ratio based on the COSMIC dataset with that based on the reanalysis, and assuming that the reanalysis is reliable in the NH, the real strength of the SH storm tracks as well as the bias in the SH in the reanalysis can be inferred. In this way, it is found that the amplitude of the SH storm tracks in the NCEP-NCAR reanalysis is significantly biased low by at least 25% at 300 mb. The amplitudes in the ERA40 and the ERA-Interim reanalyses are close to that inferred from COSMIC observations, except that the SH storm tracks in ERA40 may be biased low by about 5–10%.

[18] This work gives the first quantitative estimate of the true amplitude of the SH storm tracks made independent of numerical model outputs. In addition to exploring the biases in the reanalyses, our results can also be applied to assess whether the storm track amplitudes in GCM simulations are realistic or not. In addition, our results show that NCEP-NCAR data suggest a significant increasing trend in SH storm track activity since 1979, which is absent in ERA40 data. Further studies are being conducted to assess whether this trend is real.

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