P5.9 Tornado frequency trend and large scale environments over Ontario, Canada

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1. Introduction

Tornado has high impacts on Canadian society in terms of loss of life and damage of property. In Canada, during an average year about 80 tornadoes have been reported that result in, on average, 2 deaths, 20 injuries, and tens of millions of dollars in property damage. Because of its small-scale nature, tornado is a localized short-lived phenomenon and it is therefore difficult to detect and predict. Up to date, the detection and prediction of tornado are almost solely relied on observations and related analyses. Since tornadoes are not well resolved by most (if not all) observational networks due to lack of sufficient spatial and temporal resolutions, an alternative approach is to anticipate larger scale environments that are favorable for tornadogenesis. Numerous studies have been documented on synoptic-scale environments for tornado development (e.g., Homar et al., 2001; Tyrrell, 2007; Rasmussen et al., 2000; Roebber et al., 2002). These synoptic-scale environments associated with tornado development include, but not limited to, low-level circulation systems (e.g., Homar et al., 2001; Tyrrell, 2007), and baroclinicity (e.g., Rasmussen et al., 2000). However, these researches are mainly based on case studies. There is little work to look at these environments from a climatological point of view. Hence, it is important to gain experiences through analysis of tornado climatology and its association with large scale environments. In this study, we have detected an upward trend of tornado frequency over Ontario, Canada. Furthermore, we have examined Ontario tornado frequency variability and its relationships with large scale atmospheric conditions, such as low-level pressure systems, and baroclinicity, through composite analyses. As the first step toward the second objective, we focus on these qualitative relationships in this study.

2. Data

The quality-controlled data for tornado events and days over Ontario are obtained from Newark (1984) and the Ontario Storm Prediction Center (OSPC) of Environment Canada, respectively. The data set contains numbers of tornado events (i.e., one event is for one tornado) and days over 58 years (1950-2007), in which Newark's (1984) dataset covers the period before 1979 and the OSPC dataset covers the rest of the whole period. Ontario is geographically located between Hudson Bay and the Great Lakes. To the north of 46°N, Ontario's west-east area extent is from 96°W to 79°W, and to the south of 46°N, its eastern boundary is extended to approximately 74°W. It is well known that the US and Canadian tornado

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databases are subject to various biases (Newark 1984; Grazulis et al. 1993; Snider 1977) such as population biases due to regions with greater population densities reporting more events, and F-scale reporting biases due to weaker tornadoes with less damage being less likely reported than stronger tornadoes. The population bias was taken into account in Newark's (1984) work. Furthermore, since 1979 tornado sightings were routinely archived by Environment Canada and in 1985 the first Doppler radar was used over Ontario. Therefore, the frequency data may be reasonably representative of the actual numbers of tornado events (Etkin et al. 2001; Sills et al. 2004) although caution must be exercised when one deals with the tornado dataset. In this work, we are interested in all F-scale tornadoes because there is only few F2 or stronger tornado occurred every year in Ontario. The reanalysis data are obtained from the National Centers for Environmental Prediction (NCEP). The NCEP data are available from year 1948 to 2008. These analyses are archived with a horizontal resolution of 2.5^{o} latitude × 2.5^{o} longitude, and 17 constant pressure levels at 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa (Kalnay et al. 1996). The period of 1950-2007 is examined for details.

3. Tornado frequency trend

To detect if there exists a tornado frequency trend over the last 58 years in Ontario (see Fig. 1a), we have employed the widely-used nonparametric MK (Mann 1945; Kendall 1975) statistical test. Under the null hypothesis H_o that a sample of data $\{X_i, i=1,2,\ldots,n\}$ is independent and identically distributed, the MK test statistic S is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(X_j - X_i), \qquad (1)$$

where

$$\mathrm{sgn}(\theta) = \begin{cases} 1 & if \quad \theta > 0 \\ 0 & if \quad \theta = 0 \\ -1 & if \quad \theta < 0 \end{cases}. \qquad (2)$$

Mann (1945) and Kendall (1975) showed that when n ≥ 8, the statistic S is approximately normally distributed with the mean and the variance as follows:

$$E(S) = 0, \qquad (3)$$

$$\sigma_S^2 = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t_i + 5) \right], \qquad (4)$$

where m is the number of tied (i.e., equal values) groups, and t_i is the number of data points in the ith tied group. Under the null hypothesis, the standardized MK statistic Z follows the standard normal distribution with mean of zero and variance of one:

$$Z = \begin{cases} (S-1)/\sigma_S & if \quad S > 0 \\ 0 & if \quad S = 0 \\ (S+1)/\sigma_S & if \quad S < 0 \end{cases}. \qquad (5)$$

If $|Z| > Z_{1-\alpha/2}$, a trend is statistically significant at a level of 1-α/2.

Because the existence of positive serial correlation in a time series increases the probability of detection of a significant trend by the MK test, von Storch (1995) suggested to remove the AR(1) (a lag one autoregressive process) from the time series through a pre-whitening procedure. However, this pre-whitening also removes a portion of the trend as demonstrated by Yue and Wang (2002). To detect a trend properly, we use a trend-free pre-whitening approach (e.g., Cao 2008; Yue and Wang 2002) described in the following four procedures:

(a) A none-zero slope β of a trend in a time series $\{X_t, t=1,2,\ldots,n\}$ is estimated by a regression method, and the sample data are detrended

$$X_t^{'} = X_t - T_t = X_t - \beta t \; ; \qquad (6)$$

(b) A lag-one serial correlation coefficient ρ_1 of the detrended series $X_t^{'}$ is calculated and the AR(1) is removed from the $X_t^{'}$

$$Y_t^{'} = X_t^{'} - \rho_1 X_{t-1}^{'} \; ; \qquad (7)$$

(c) The identified trend T_t and the residual $Y_t^{'}$ are blended

$$Y_t = Y_t^{'} + T_t \; ; \qquad (8)$$

(d) The MK test is then applied to the blended series to assess the significance of the trend.

It is noted that the blended series Y_t could preserve the true trend and is no longer influenced by the effects of autocorrelation.

As shown in Table 1, the computed Z statistic is greater than $Z_{1-\alpha/2}$ at different significant levels. It is demonstrated that the upward trend of Ontario tornado frequency is at least significant at the level of 95%. After removing the AR(1) process, we have plotted this upward trend of tornado frequency in Fig. 1b. Based on our calculation, the trend is about 1.6/decade with the statistically significant level at least at 95%. This statistically significant upward trend is also identified by the second independent approach, i.e., the conventional linear regression method.

4. Tornado frequency variability

As shown in Fig. 1a, there are substantial decadal variabilities in Ontario tornado frequency over the last almost six decades. These variabilities in numbers of tornado events are similar to those in numbers of tornado days. The correlation between the numbers of tornado events and the numbers of tornado days is 0.90 with statistically significant level greater than 99%. To better visualize the tornado event frequency, we sort the original tornado events in an ascending order and present them in a form of the anomaly with a mean of 13.8 (Fig. 1c). As observed from Fig. 1c, there are a number of years with positive and negative anomaly of tornado events. The 20 strong positive anomaly years appear in 2006, 1969, 1985, 1982, 1981, 2001, 1980, 1968, 1983, 1978, 1966, 1973, 1979, 1994, 1997, 1977, 1987, 1998, 1999, and 1984, referred to as high-event years, whereas the 20 strong negative anomaly years appear in 1955, 1963, 1989, 1950, 1972, 1974, 1951, 1952, 1958, 1962, 1975, 1988, 1956, 1960, 1961, 1990, 2007, 1954, 1964, and 1965, referred to as low-event years.

To understand how the tornado frequency is linked with large scale atmospheric conditions such as low-level circulation systems, and baroclinicity, we employ monthly mean NCEP reanalysis data for a simple composite of anomalies for geopotential height (1000-hPa) and thickness (1000-500 hPa) during the high-event and low-event years. Since tornadoes in Ontario almost all occur from March to September (Etkin et al. 2001), composite analyses are performed over these 7 months. As displayed in Fig. 2, the geopotential height (1000-hPa) anomalies vary from -2 to 0 m across the whole Ontario in the high-event years whereas in the low-event years they change from -0.5 to 2 hPa. This indicates that the high-event years are associated with more anomalous cyclonic circulations than the low-event years. This finding is consistent with the fact that synoptic-scale environments for tornado development are usually associated with low pressure systems (e.g., Homar et al., 2001; Tyrrell, 2007).

Figure 3 shows thickness (1000-500 hPa) anomalies during the high-event and low-event years, respectively. In the high-event years, the thickness (1000-500 hPa) anomalies are positive over Ontario (Fig. 3a). During the low-event years, the thickness anomalies are negative over Ontario (Fig. 3b). The value of the positive anomaly in the high-event years ranges from 2 to 8 m while the value in the low-event years varies from -4 to -7 m. It is interesting to note that the north-south thickness difference across the whole Ontario is 6 m in the high-event years whereas it is -3 m in low-event years. Based on the thermal wind relationship, the thickness (1000-500 hPa) is proportional to the mean temperature between 500 and 1000 hPa. This indicates that the high-event years are linked to the warmer temperature whereas the low-event years are associated with the cooler temperature over Ontario. Since the magnitude of the north-south thickness difference in the high-event years is more than that in the low-event years, it is suggested that over the Ontario region, much stronger baroclinicity is associated with the high-event years than that in the low-event years. Hence, the large scale atmospheric conditions associated with both warmer air temperature and stronger low-level baroclinicity are favorable for more tornadogenesis. Because the horizontal baroclinicity is proportional to a vertical wind shear, one of the important elements for tornado development, our results from a climatological point of view confirm the importance of baroclinic environments to tornado development. This importance has also been verified at synoptic scales (e.g., Rasmussen et al., 2000).

5. Conclusions

In this study, we have examined Ontario tornado frequency changes over the last almost six decades. It is found that over the last almost six decades the tornado frequency has an increasing trend. The robustness of this upward trend is established through the MK statistical test with consideration of removing the AR(1) process. It is also found that Ontario tornado frequency has substantial variabilities during the past 58 years. The qualitative connection of decadal variability of Ontario tornado frequency to large scale atmospheric conditions is investigated. It is shown through a composite analysis that in the warming climate the strong low-level cyclonic systems and baroclinicity are favorable for more frequent tornado occurrence over Ontario, Canada.

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References

Cao, Z., 2008: Severe hail frequency over Ontario, Canada: recent trend and variability. *Geophys. Res. Lett.* **35**, L14803, doi:10.1029/2008GL034888.

Etkin, D., S. E. Brun, A. Shabbar, and P. Joe, 2001: Tornado climatology of Canada revisited: tornado activity during different phases of ENSO. *Int. J. Climatol*. **21**, 915-938.

Grazulis, T. P., J. T. Schaefer, and R. F. Abbey, 1993: Advances in tornado climatology, hazards, and risk assessment since Tornado Symposium II. In The Tornado: Its Structure, Dynamics, Prediction and Hazards. Geophysical Monograph. 79, Church C, Burgess D, Doswell C, Davies-Jones R (eds), American Geophysical Union, 409-426.

Homar, V., M. Gayà, C. Ramis, 2001: A synoptic and mesoscale diagnosis of a tornado outbreak in the Balearic Islands. *Atmos. Res*. **56**, 31-55.

Kalnay, E., and co-authors, 1996: The NCAP/NCAR 40-year reanalysis project. *Bull. Am. Meteorolo. Soc.* **77**, 437-471.

Kendall, M. G., 1975: Rank Correlation Methods. Charles Griffin, 202 pp.

Mann, H.B., 1945. Nonparametric test against trend. Econometrica. 13, 245-259.

Newark, M. J., 1984: Canadian tornadoes, 1950 to 1979. *Atmos.-Ocean*. **22**, 343-353.

Rasmussen, E. N., S. Richardson, J. M. Straka, P. M. Markowski, D. O. Blanchard, 2000: The association of significant tornadoes with a baroclinic boundary on 2 June 1995. *Mon. Wea. Rev*. **128**, 174-191.

Roebber, P. J., D. M. Schultz, and R. Romero, 2002: Synoptic regulation of the 3May 1999 tornado outbreak. *Wea. Forecasting*. **17**, 399-429.

Sills, D .M. L., S. J. Scriver, and P. W. S. King, 2004: The Tornadoes in Ontario Project (TOP). 22nd AMS Conference on Severe Local Storms. Amer. Meteorol. Soc. CD-ROM Paper 7B.5.

Snider, C.R., 1977: A look at Michigan tornado statistics. *Mon. Wea. Rev*. **105**, 1341-1342.

Tyrrell, J., 2007: Winter tornadoes in Ireland: The case of the Athlone tornado of 12 January 2004. *Atmos. Res*. **83**, 242-253.

von Storch, H., 1995: Misuses of statistical analysis in climate research, in *Analysis of Climate Variability Applications of Statistical Techniques*, edited by H. von Storch and A. Navarra, Springer, New York, pp. 11-26.

Yue, S., and C. Y. Wang, 2002: Regional streamflow trend detection with consideration of both temporal and spatial correlation. *Int. J. Climatol*. **22**, 933-946.

Table 1 Mann-Kendall test for trend detection of Ontario tornado frequency

Z statistic	2.62	-	-
$Z_{1-\alpha/2}$	2.58	1.96	1.65
α	0.01	0.05	0.10

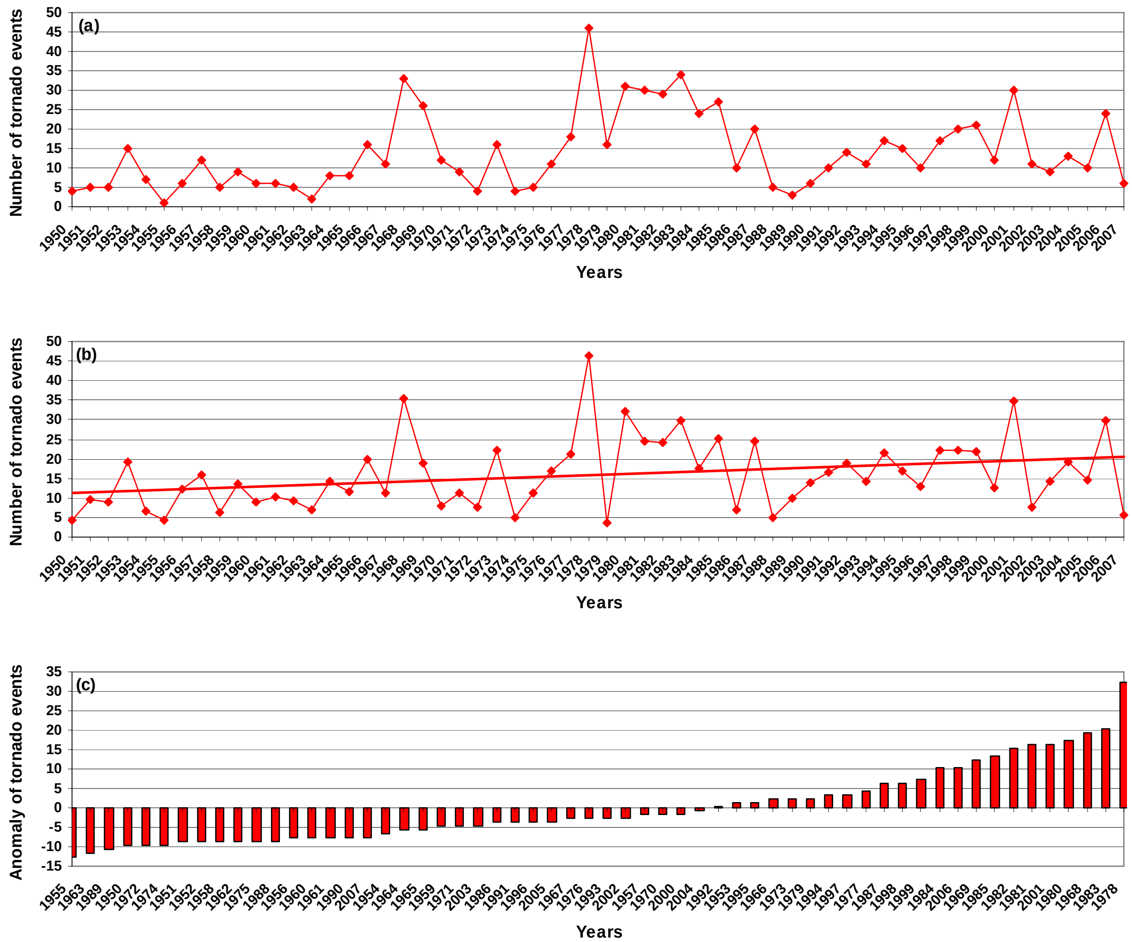

Fig. 1 (a) Time series of tornado event number (1950-2007) over Ontario, Canada; (b) The time series of tornado event number (1950-2007) over Ontario and its trend after removing the AR(1) process; (c) Same as (a) except the anomaly of tornado event number being sorted in an ascending order.

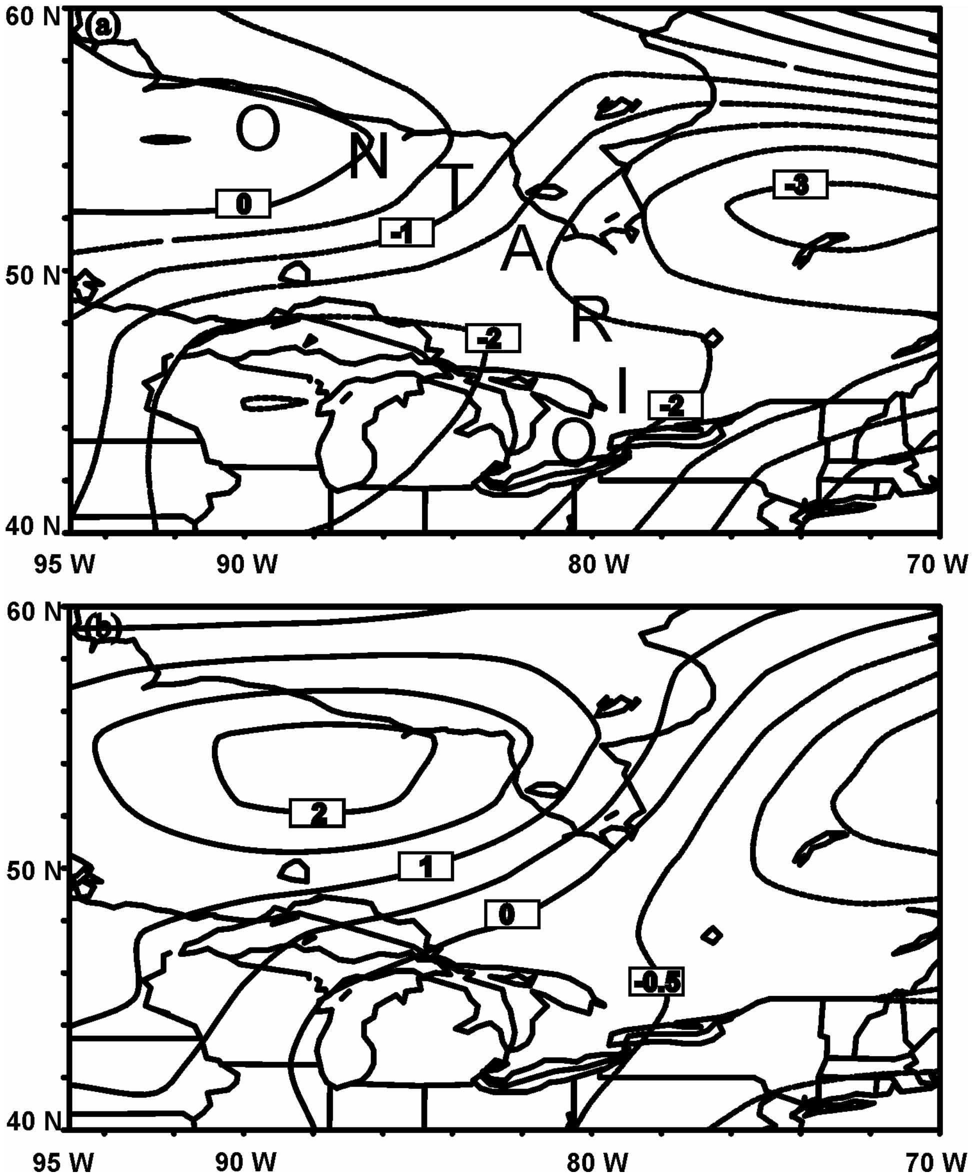

Fig. 2 Geopotential height (1000 hPa) anomaly (m) over Ontario, Canada in (a) the high-event years and (b) the low-event years.

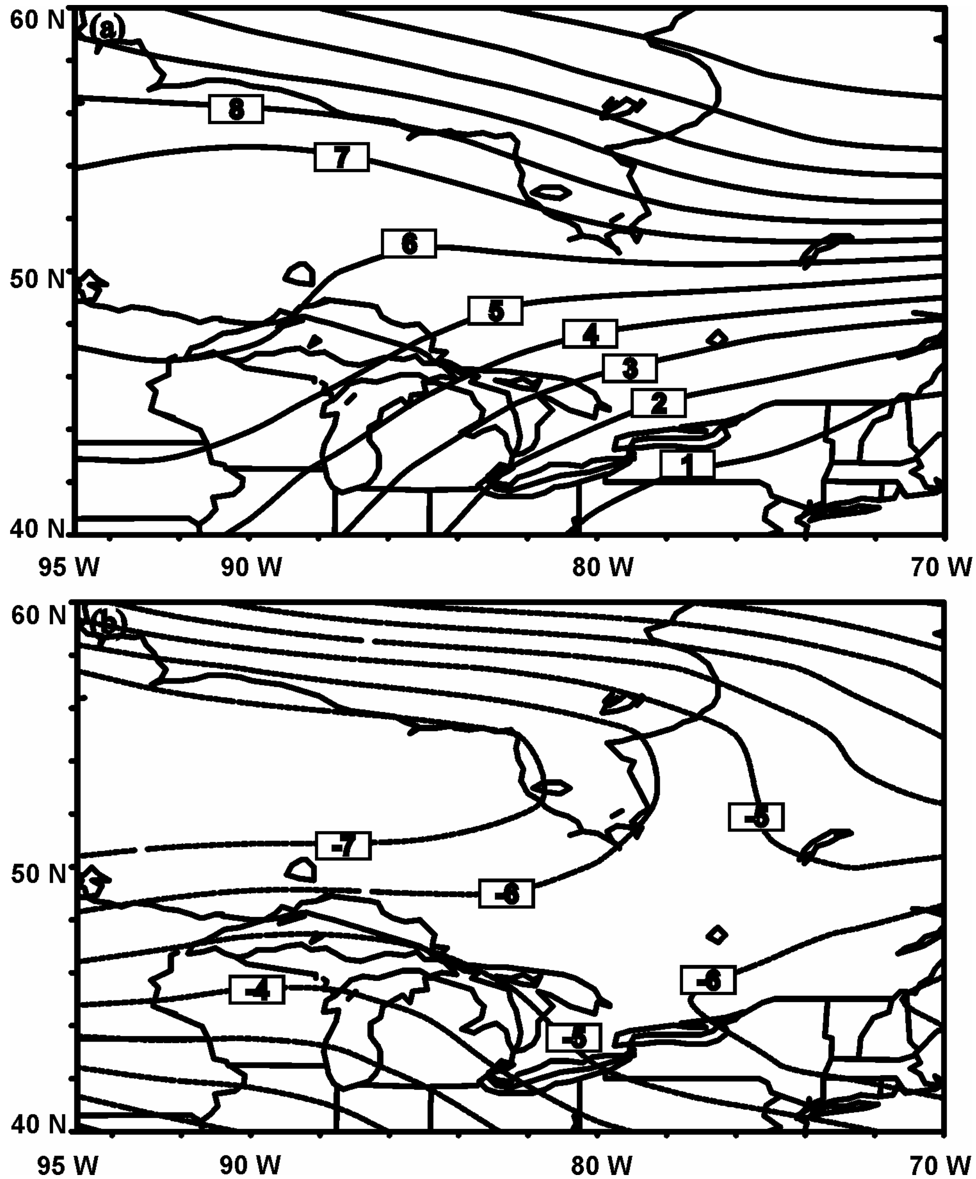

Fig. 3 Same as Fig. 2 except for thickness (1000-500 hPa) anomaly (m).