Climatology and Predictability of the Late Summer Stratospheric Zonal Wind Turnaround over Vanscoy, Saskatchewan

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ABSTRACT *A climatology of the late summer stratospheric zonal wind turnaround phenomenon is presented, with a particular focus on the behaviour over the Meteorological Service of Canada's balloon-launching site at Vanscoy, Saskatchewan (52°N, 107°W). Turnaround refers to the change in sign of the zonal wind velocity and occurs twice each year at stratospheric mid-latitudes, in early spring and in late summer. The late summer turnaround is of particular interest to the high-altitude ballooning community because it offers the ideal conditions for launch, but it is also an interesting dynamical phenomenon in its own right. It is studied here using both the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis and the United Kingdom Meteorological Office (MetO) analysis products as well as climate simulation data from the Canadian Middle Atmosphere Model (CMAM). The phenomenon and its interannual variability are documented. The predictability of the late summer turnaround over Vanscoy is investigated using both statistical averages and autocorrelation analysis. From the statistical averages, it is found that during every year since 1993, the period from 26 August to 5 September has contained appropriate launch dates. From the autocorrelation analysis, it is found that stratospheric zonal wind anomalies can persist for a month or more during most of the summer, but there is a predictability horizon at the end of the summer — just before turnaround*

RESUMÉ *[Traduit par la rédaction] On présente une climatologie du phénomène de renversement du vent zonal stratosphérique à la fin de l'été, en s'intéressant plus particulièrement au comportement au-dessus du site de lancement de ballons du Service météorologique du Canada de Vanscoy, en Saskatchewan (52°N, 107°O). Le renversement en question est un changement de signe de la composante zonale du vent et il se produit deux fois par année dans les latitudes moyennes stratosphériques, au début du printemps et à la fin de l'été. Le renversement de la fin de l'été présente un intérêt particulier pour les gens qui lancent des ballons de haute altitude car il offre des conditions de lancement idéales, mais c'est aussi un phénomène dynamique intéressant en lui-même. On l'étudie ici en utilisant à la fois les produits d'analyse du National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis et du United Kingdom Meteorological Office (MetO) de même que des données de simulation climatique du Modèle canadien de l'atmosphère moyenne (CMAM). Le phénomène et sa variabilité interannuelle sont documentés. On étudie la prévisibilité du renversement de la fin de l'été au-dessus de Vanscoy en se servant à la fois de moyennes statistiques et d'analyses d'autocorrélation. Les moyennes statistiques montrent que chaque année depuis 1993, la période du 26 août au 5 septembre contient des dates de lancement appropriées. D'autre part, l'analyse d'autocorrélation montre que les anomalies du vent zonal stratosphérique peuvent persister pendant un mois ou plus la plupart des étés, mais il y a un horizon de prévisibilité à la fin de l'été — juste avant le renversement.*

1 Introduction and motivation

Vanscoy, Saskatchewan (52°N, 107°W) is the launch site for the Middle Atmosphere Nitrogen TRend Assessment (MANTRA) high-altitude balloon campaigns, which took place in the late summers of 1998, 2000 and 2002, with a fourth campaign planned for 2004 (Strong et al., this issue). The scientific objective of MANTRA is to study the changing chemical balance of the stratosphere at northern mid-latitudes, with a particular focus on the nitrogen budget and its role in the depletion of mid-latitude ozone. The original motivation for developing a climatology of winds over the launch site was to determine how early, and with what accuracy, it is possible to predict the optimal launch date in terms of stratospheric winds. Ideally, the balloons should be launched when the stratospheric wind speeds are at a minimum in order to ensure that the payload remains within the telemetry range (approximately 500 km) for the duration of mission science

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(typically 18 hours). The MANTRA balloons normally float at a height of 35–40 km, or about 5 mb.

In the extratropical stratosphere, there is a marked annual cycle in temperature in both hemispheres. At solstice, the highest temperatures occur over the summer pole and the lowest temperatures occur over the winter pole. It then follows from the thermal wind equation that there will be easterly zonal winds in the summer hemisphere and westerlies in the winter hemisphere. Easterlies forbid the propagation of stationary Rossby waves (Charney and Drazin, 1961), and the summer stratosphere is therefore relatively quiescent. In contrast, westerlies permit the propagation of stationary Rossby waves of sufficiently large scale, and the winter stratosphere is regularly disturbed by planetary waves. Extratropical stratospheric zonal winds change sign during so-called ‘turnaround’ events twice a year, in early spring and in late summer. The springtime transition is highly irregular, because of the wintertime variability in vortex conditions induced by planetary-wave forcing, but the late-summer transition is comparatively smooth. This contrast between the two events in the northern hemisphere is clearly visible in Fig. 1, which shows the climatology of 10-mb zonal winds over Vanscoy using three different data sources (discussed below).

The scientific objectives of MANTRA are more readily met by a launch during late summer, which is dynamically quiescent and closer to photochemical control (Fahey et al., 2000; Fioletov and Shepherd, 2003). A late-summer launch is also preferred from the standpoint of winds, given that there is far less variability in the late summer turnaround event than in that of early spring (Fig. 1). The purpose of this paper is to characterize the late-summer turnaround event, which does not appear to have been previously studied, and in particular to investigate how far in advance it can be predicted.

2 Datasets

The zonal wind datasets used in this study include assimilated data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis project (Kalnay et al., 1996) and the United Kingdom Meteorological Office (MetO) (Swinbank and O’Neill, 1994; Lorenc et al., 2000), as well as model data from climate simulations performed with the Canadian Middle Atmosphere Model (CMAM).

The NCEP/NCAR Reanalysis data are provided by the Climate Diagnostics Center with 6-hourly data combined into a daily average zonal wind over a grid of 144 longitudes by 73 latitudes, on 17 pressure levels, for the period 1948–2003. The closest grid point to Vanscoy is (52.5°N, 107.5°W). The reanalysis data have several limitations from the perspective of this study. Most importantly, its ceiling is 10 mb, while the MANTRA balloons float at about 5 mb. As noted by Trenberth and Stepaniak (2002), the 10-mb flow in the reanalysis is corrupted over topography; this should not be a problem over Vanscoy which is located on the Canadian Prairies. We have used the reanalysis record from 1979 onward since satellite data were integrated into the model at that time (Kalnay et al., 1996), and because the focus of this work is on predicting the turnaround phenomenon over Vanscoy for future launches. The effect of including the entire record is addressed in Section 4b.

The MetO dataset used in this study is a stratospheric extension of the MetO weather forecasting operational analysis (Swinbank and O’Neill, 1994). The MetO lid is at 0.32 mb. The closest grid point to Vanscoy is (52.5°N, 108.75°W). However, the MetO dataset only starts in late 1991, which places limitations on the statistical analysis. The MetO and NCEP/NCAR datasets were compared for coincident years at 10 mb, and the results are shown in Fig. 2. NCEP/NCAR zonal winds at 10 mb are generally more westerly than MetO zonal winds by about 2 m s^{-1}, on average, and differences can often reach 5 m s^{-1}. Turnaround in the late summer is relatively barotropic above 10 mb (see Fig. 3); thus, because of the overall similarity of the MetO and NCEP/NCAR datasets at 10 mb, we have primarily used the NCEP/NCAR dataset at 10 mb, to take advantage of its longer data record. However, in light of the differences with MetO, we ensure that all conclusions are also supported by the MetO data.

The CMAM is a three-dimensional climate simulation model with fully interactive chemistry that extends from the surface of the Earth to approximately 100 km altitude (0.001 mb) (Beagley et al., 1997; de Grandpré et al., 2000). It contains a representation of the relevant physical processes in this region. The non-orographic gravity-wave drag scheme used is that of Hines (1997), and its implementation in CMAM is described by McLandress (1998). The simulation analysed here is described as the ‘2000 run’ in Austin et al. (2003), corresponding to current atmospheric conditions, and has T32 horizontal spectral truncation (corresponding to a grid spacing of about 5.5°) and 65 vertical levels. Sea surface temperature distributions are specified from the observed climatology of Shea et al. (1990), and repeated for every year of the simulation. The years analysed here are the last 24 of a 39-year simulation. The closest CMAM grid point to Vanscoy is (50.625°N, 108.75°W); the data are output every 18 hours.

3 Climatology

The vertical–temporal structure of turnaround over Vanscoy is shown in Fig. 3a based on the NCEP/NCAR data; Fig. 3b uses the MetO data and Fig. 3c uses CMAM data. At and below 100 mb, the zonal winds are westerly throughout the year, with a maximum around 300 mb at the jet stream. Above about 70 mb (approximately 25 km), the zonal winds change sign twice each year and turnaround events can be defined. The zero contour is almost vertical, indicating that turnaround occurs simultaneously at all altitudes. None of the other contours shows such a vertical alignment penetrating so deeply into the middle stratosphere, suggesting that the zero contour is special.

Figure 1a shows the range of variability in zonal winds at 10 mb over Vanscoy, using the NCEP/NCAR Reanalysis data. According to the figure, the climatological mean zonal

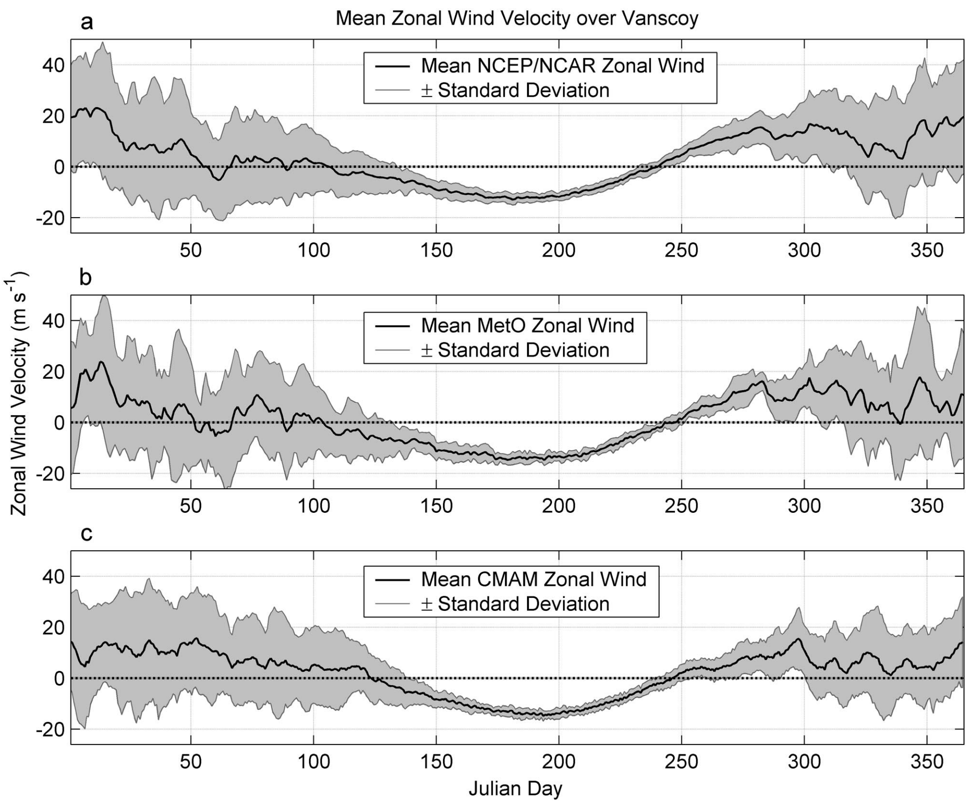

Fig. 1 Long-term mean of the 10-mb zonal wind over Vanscoy (solid curve), and standard deviation of the daily data (shading): a) data from the NCEP/NCAR Reanalysis (1979–2003); b) data from the MetO analysis (1993–2002); and c) the 24-year CMAM model run for current conditions.

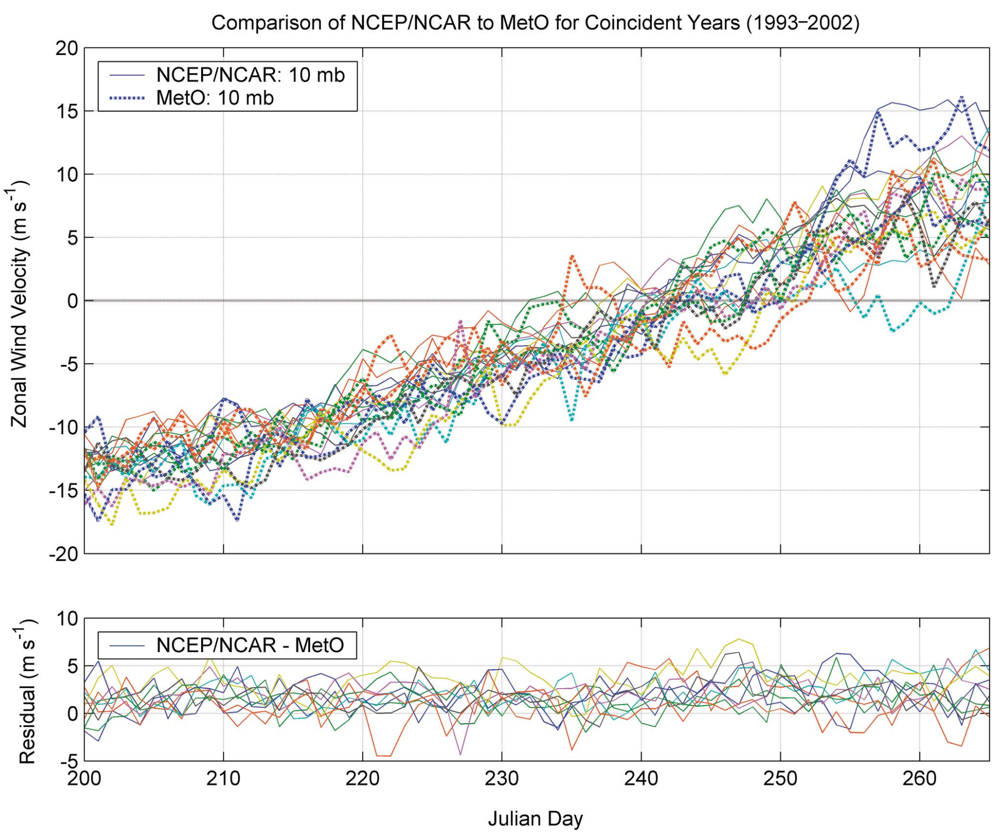

Fig. 2 A comparison of coincident years of zonal wind velocity at 10 mb over Vanscoy for the NCEP/NCAR (solid) and MetO (dotted) assimilated datasets. The different colours correspond to different years. The residuals (MetO data subtracted from NCEP/NCAR) are plotted in the lower panel and show a bias but no particular trend.

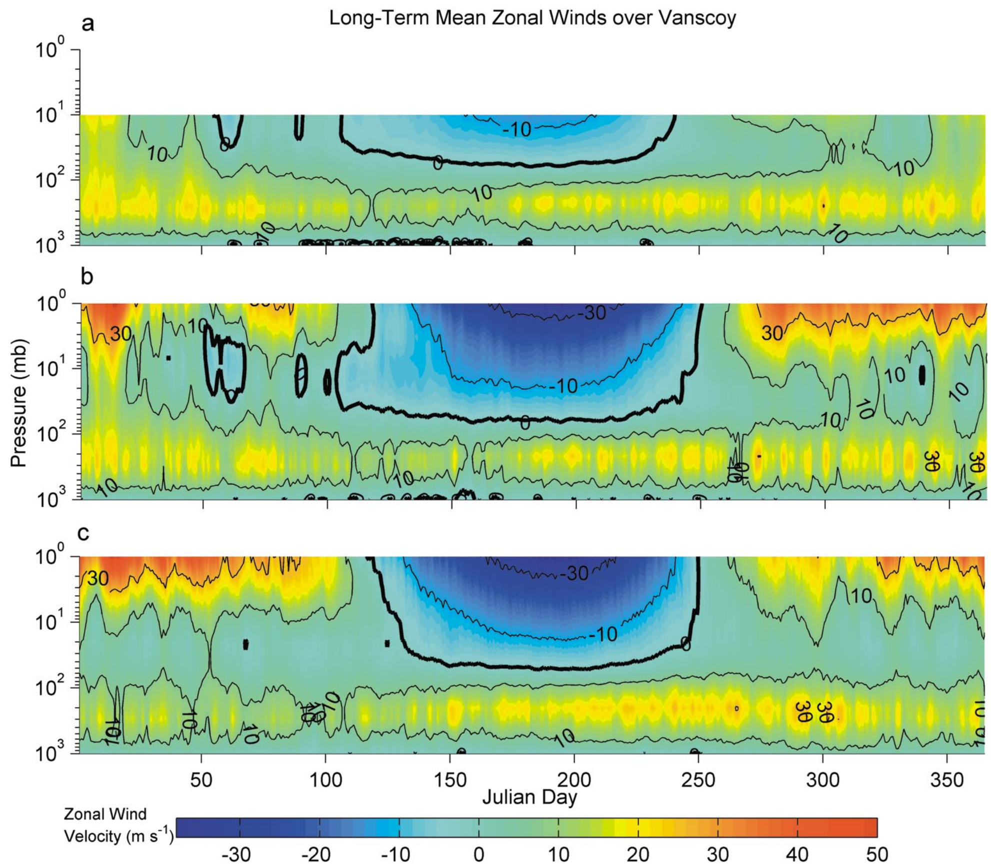

Fig. 3 Long-term mean zonal wind velocity over Vanscoy as a function of pressure level and Julian day: a) NCEP/NCAR data including years 1979–2003 on 17 pressure levels; b) MetO data including years 1993–2002 on 22 pressure levels; and c) CMAM data using 24 years at 16 pressure levels relevant to this study. The thick black line indicates the zero contour.

wind crosses the zero line from easterly to westerly at day 239, with a standard deviation of 10.8 days. The corresponding date from MetO data (Fig. 1b) is day 247.2, with a standard deviation of 4.7 days. The CMAM zonal winds (Fig. 1c) cross the zero line around day 246.1, with a standard deviation of 7.6 days. During the period of relative quiescence from about day 130 to day 250 (10 May to 7 September), when the zonal wind is easterly and planetary waves are evanescent, the stratosphere is close to radiative equilibrium and one would hope it would be well simulated by a climate model. Indeed, during this period the CMAM (which simulates current conditions) agrees well with the MetO assimilated data for 1993–2002.

The excellent agreement between CMAM and MetO during summer is highlighted in Fig. 4, which shows the long-term mean zonal wind speed over Vanscoy for each dataset, based on daily values. (For MetO and CMAM, these are the same means as shown in Fig. 1.) Only the NCEP/NCAR data with years corresponding to the MetO dataset are included in the figure in order to determine if the discrepancy between the turnaround dates for these two datasets is dependent on the years used. The mean turnaround dates from this figure are 240.9 for NCEP/NCAR versus 247.2 for MetO. We can therefore conclude that the difference is not solely due to the time period. There is also no significant change to the zonal wind means with interpolation to a common latitude and longitude. This comparison highlights the systematic westerly bias of NCEP/NCAR vis-à-vis MetO during the summer of about 2 m s^{-1}, leading to a turnaround date that is earlier by about one week. During the disturbed winter–spring period, the agreement between NCEP/NCAR and MetO is much better than during the summertime period.

The spring turnaround has greater interannual and day-to-day variability than the late summer turnaround. Because of the strong variability during the winter months, it is difficult to define the climatology of the wintertime Arctic vortex, certainly in the daily data as exemplified in mid-latitudes by Fig. 1, and even in the monthly mean data (Scaife et al., 2000). This sensitivity comes from the inherently chaotic nature of planetary-wave variability (Scott and Haynes, 2000; Yoden et al., 2002) and represents a significant challenge for model validation (Austin et al., 2003). During the winter–spring period CMAM agrees with the two assimilated datasets within the variability.

Figure 5 shows the time evolution of the horizontal spatial structure of the zonal winds at the 10-mb level over North America. Zonal winds are shown from Julian day 235 to 260 (23 August to 17 September) for 1998: the year of the first MANTRA launch. The zero contour (black curve) first

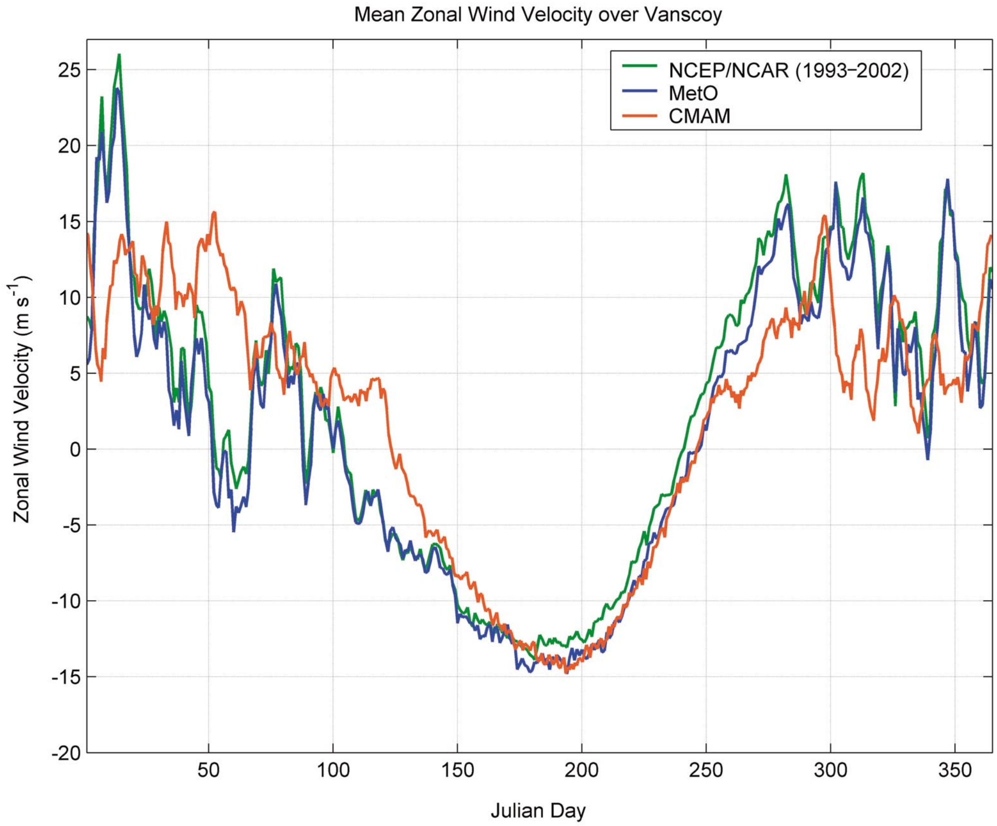

Fig. 4 A comparison of NCEP/NCAR (1993–2002) (green), MetO (1993–2002) (blue) and CMAM (24 years) (red) long-term means of 10-mb zonal wind velocity over Vanscoy.

appears in small isolated closed loops at high latitudes (between 50°N and 80°N) in late August. These loops are relatively evenly distributed zonally across the planet. The zero contours then coalesce into a distinct line, which is roughly zonally symmetric, between 45°N and 55°N. This zero contour drifts uniformly south for several weeks, to a latitude of about 30°N in early October. The white curve is the 10 m s^{-1} contour and the red curve is –10 m s^{-1}.

Due in part to the day-to-day variability in the zonal wind, there is considerable year-to-year variability in the length of the late-summer turnaround phenomenon. In some years, the winds change quickly from easterly to westerly, with the time series only crossing the zero line once. In other years, the wind speeds hover around zero for longer. Figure 6 shows the late-summer turnaround event for two sample cases. In 1987, the transition across the zero line occurred over a period of somewhat longer than one month, while in 1985 it occurred over roughly five days.

In order to characterize turnaround objectively as an extended phenomenon, an interval was defined for each year during which the sign of the zonal wind was in the process of change. This approach allowed for the accommodation of the observed variability in the winds. The turnaround interval is defined here as the set of days in late summer that lie between the first day for which $u \geq -4$ m s^{-1} and the last day for which $u \leq +4$ m s^{-1}, where u is the 10-mb zonal wind over Vanscoy. The value of 4 m s^{-1} was chosen to ensure that the MANTRA balloon reaches neither Lake Winnipeg nor the Rocky Mountains during its flight — two undesirable payload recovery sites. If there are two or more distinct time intervals during late summer satisfying this condition, separated from each other by four or more days, then only the time interval that involves a crossing through the transition range of u, rather than a temporary ingression into the transition range, is considered. This procedure ensures that the turnaround interval defined for a given year is not artificially lengthened by anomalously low wind speeds well before or well after turnaround. Although not every day within the turnaround interval in a given year has low wind speeds, if a day within the interval has strong winds, then there are days in close proximity on either side for which the wind speeds are very low or vanishing. From the perspective of ballooning, the turnaround interval defined here is one in which good launch days are likely.

Figure 7 shows the duration of the late summer turnaround interval at 10 mb, defined using the above procedure, for each dataset. There does not seem to be any significant relationship between the length and the timing of turnaround. Each day in late summer was assigned a score according to the number of years that day fell within the turnaround interval. Figure 8 shows the normalized distribution of scores for the late summer. The mean of the distribution for NCEP/NCAR is day 239.3; the standard deviation is 7.6 days. The mean for MetO

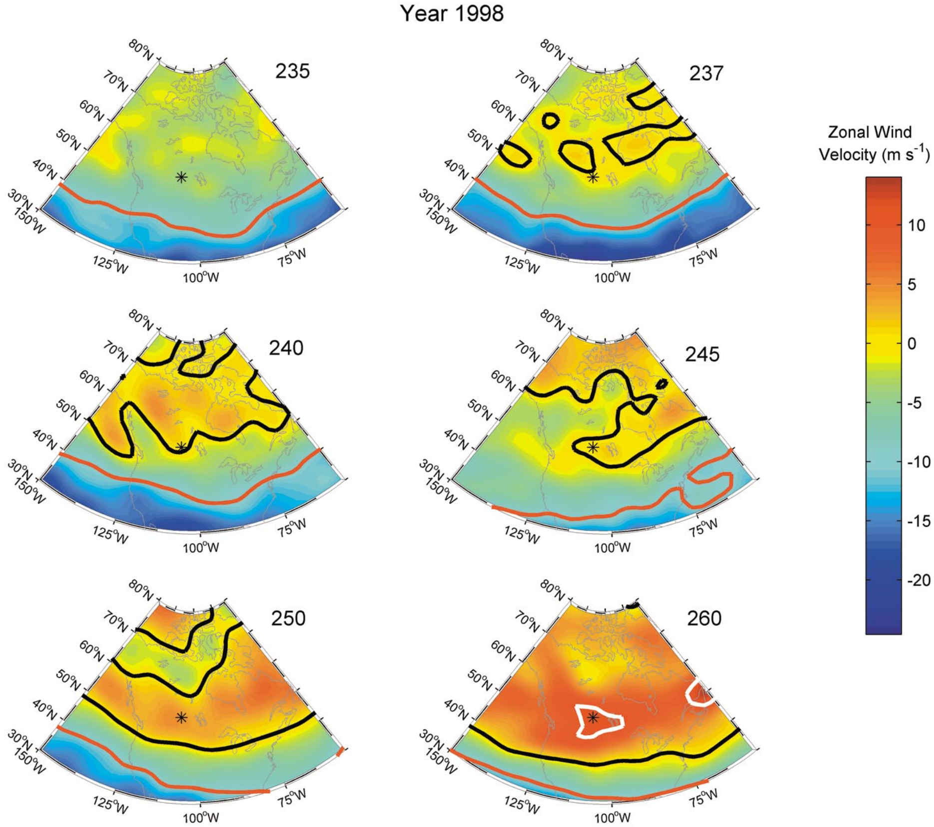

Fig. 5 Zonal wind velocity at 10 mb over North America on Julian days 235, 237, 240, 245, 250, and 260 of 1998, using the NCEP/NCAR Reanalysis data. The black asterisk marks Vanscoy, while the red, black, and white curves mark, respectively, the contours of –10, 0, and +10 m s^{-1} zonal wind velocities.

is day 245.1, and the standard deviation is 8.6 days. The distributions saturate because certain dates lie within the turnaround interval every year. Apart from this feature, both distributions appear to be consistent with Gaussian distributions. The mean for CMAM is day 246.3 with a standard deviation of 9.6 days. The CMAM distribution, however, is clearly non-Gaussian, with an unrealistically high frequency of prolonged turnaround events extending well into early autumn.

When using coincident years for NCEP/NCAR and MetO in this analysis (Fig. 8b), the NCEP/NCAR mean turnaround date is two days later, at day 241.5 (29 August). There are 11 dates that lie within the turnaround interval for every year since 1993 in both the NCEP/NCAR and MetO datasets. These dates are 238 to 248, or 26 August to 5 September. Despite the westerly bias of NCEP/NCAR with respect to MetO and the earlier mean turnaround date (even for the same years: 1993–2002), the first date with a frequency of unity (day 238) – the start of the target launch window – is the same for both datasets.

4 Predictability

The first approach to prediction considered was to examine the time lag between the peak easterly wind speed over Vanscoy in mid-summer and turnaround in late summer. This was done in order to investigate the possibility of a consistent time lag between the two phenomena from year to year. To this end, the zonal wind in each year between 1979 and 2003 of the NCEP/NCAR Reanalysis data was fitted to a fifth-order polynomial over the period of low variability in summer (days 150 to 270). The occurrence of the maximum easterly value of the zonal winds (from the fit) was then correlated with the *x*-intercept (the zero-crossing) in late summer. No significant correlation was found, and the distribution of time lags gave a mean of 54.7 days with a standard deviation, σ_{lag}, of 6.9 days. The standard deviation of the occurrence of peak easterly winds in mid-summer, σ_{peak}, was 6.3 days, while the standard deviation of the *x*-intercepts, interpreted as the incidence of turnaround, σ_{turn}, was 3.2 days. The variances are related by

$$\sigma^2{}_{lag} = \left\langle \left(x'_{turn} - x'_{peak} \right)^2 \right\rangle$$
$$= \sigma^2{}_{turn} + \sigma^2{}_{peak} - 2\left\langle x'_{turn} x'_{peak} \right\rangle,$$

where x'_{turn} is the anomalous date of turnaround (i.e., the deviation from the long-term mean) and x'_{peak} is the anomalous date of the easterly wind peak. The angle brackets represent the ensemble average, and therefore the third term on the right-hand side of the equation represents the covariance between x'_{turn} and x'_{peak}. Note that σ^2_{lag} = 47.6 d^2, while $\sigma^2_{turn}+\sigma^2_{peak}$ = 49.9 d^2, thus the two phenomena are essentially uncorrelated (i.e., $\langle x'_{turn} x'_{peak} \rangle \approx 0$). This means that there is no memory of interannual anomalies between the easterly maximum and turnaround. The years 1982 and 1997

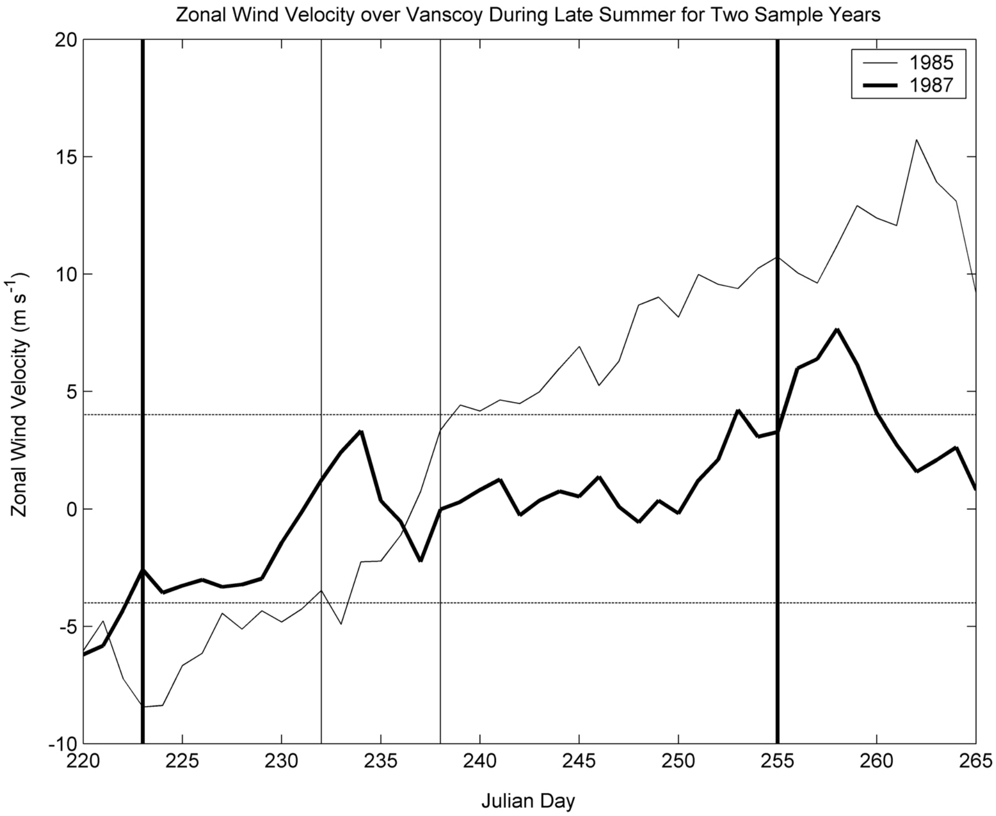

Fig. 6 Zonal wind speed at 10 mb over Vanscoy during Julian days 220–265, for sample years 1985 and 1987, using the NCEP/NCAR Reanalysis data. These curves illustrate the range of days over which turnaround occurred. The horizontal dashed lines indicate ±4 m s^{-1} and the vertical lines correspond to the earliest and latest turnaround days for each curve (see text for definition).

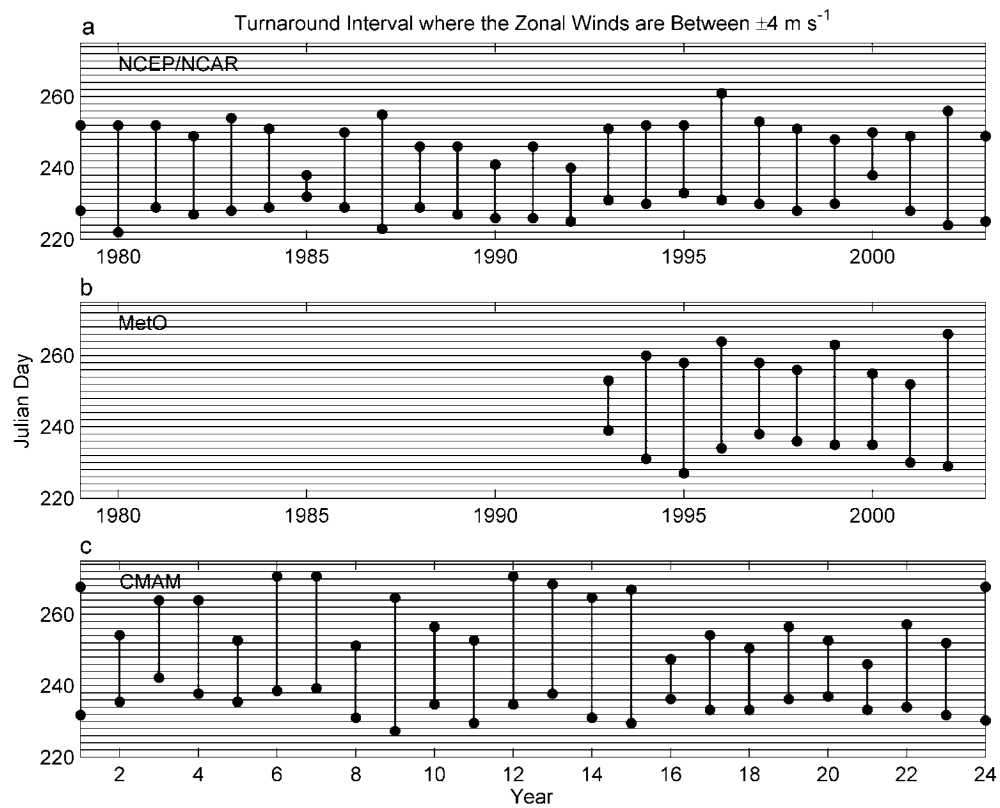

Fig. 7 The duration of the late summer turnaround measured at 10 mb. The range of days plotted for each year defines the interval of low zonal wind speed corresponding to the turnaround event: a) NCEP/NCAR Reanalysis data for years 1979–2003; b) MetO for years 1993–2002; and c) 24 years of CMAM data.

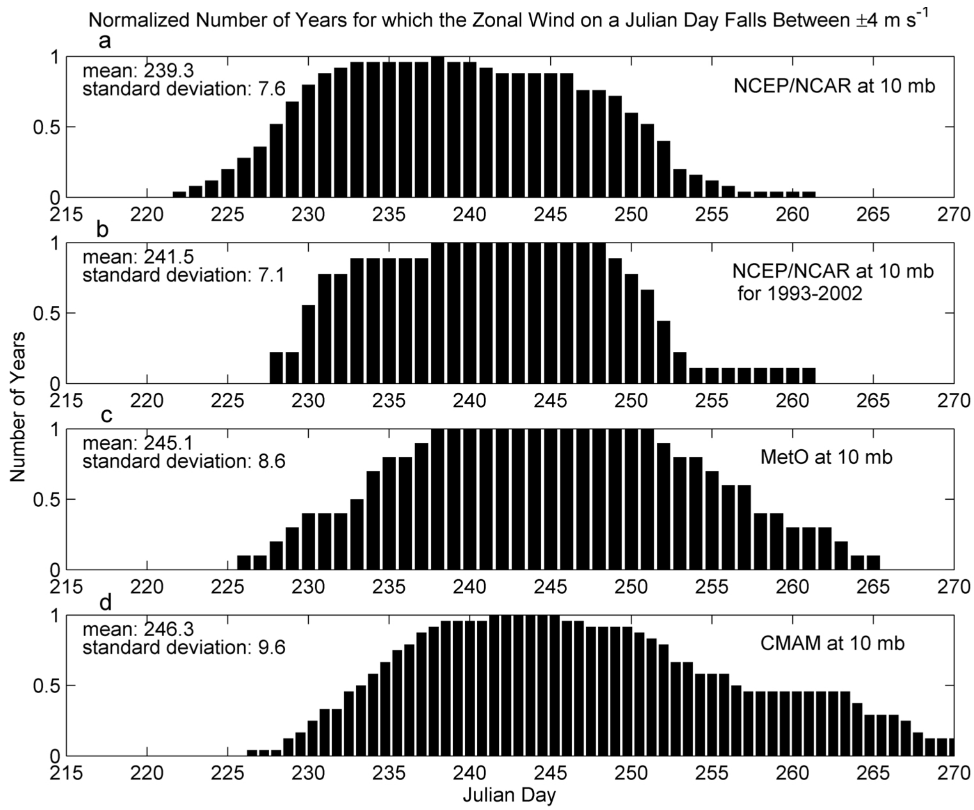

Fig. 8 Normalized probability distribution of a late-summer Julian day being within a turnaround event, using the data from Fig. 7: a) NCEP/NCAR Reanalysis data using years 1979–2003; b) NCEP/NCAR Reanalysis data using years 1993–2002; c) MetO data using years 1993–2002; and d) 24 years of CMAM data.

TABLE 1. The rows of this table list the autocorrelation coefficients for the zonal wind, *u*, over (52.5°N, 107.5°W), the correlation coefficients of the zonal mean wind, *u*, at 52.5°N, with *u*, and the autocorrelation coefficients of the zonal mean wind ($\bar{u}$ with $\bar{u}$), at three time lags, 30 days, 20 days and 10 days prior to turnaround (taken here to be the means in Fig. 8). In the second case, $\bar{u}$ leads *u*. These calculations were performed using years 1979–2003 of the NCEP/NCAR Reanalysis dataset at the 10-mb pressure level. Correlations vary from day to day (see Fig. 9 for an illustration) and only the exact day's correlation coefficient was recorded in the table. Values in bold are statistically significant at the 95% confidence level.

	30 days	20 days	10 days
Autocorrelation coefficients of zonal winds over (52.5°N, 107.5°W)	–0.286	–0.155	–0.322
Correlation coefficients of zonal mean wind at 52.5°N to the zonal winds over (52.5°N, 107.5°W)	0.050	0.171	**0.453**
Autocorrelation coefficients of zonally averaged zonal winds at 52.5°N	**0.463**	**0.536**	**0.570**

were excluded from this analysis because the easterly winds during the early summer of those years were too strong to allow for a meaningful fit over the desired range of days.

The *x*-intercepts from the fifth-order polynomial estimate turnaround at Julian day 240.7 with a standard deviation of 3.2 days. The mean is comparable to those obtained from the two methods discussed earlier, but the standard deviation is smaller. This is presumably due to the smoothing inherent in the polynomial fit.

a *Seasonal Persistence*

There has been considerable recent interest in the seasonal persistence of stratospheric dynamical regimes during wintertime (Baldwin and Dunkerton, 2001). In order to assess how much memory there is in the summertime stratospheric winds, autocorrelations were computed beginning at different times of the year, following the approach of Fioletov and Shepherd (2003) for ozone anomalies. Specifically, for a time series consisting of *n* years of data, the correlation of zonal wind at day *i* with that at day *j* is defined by

$$\frac{\sum_{k=1}^{n} u_k'(i) u_k'(j)}{\left\{\sum_{k=1}^{n} \left[u_k'(i)\right]^2\right\}^{\frac{1}{2}} \left\{\sum_{k=1}^{n} \left[u_k'(j)\right]^2\right\}^{\frac{1}{2}}},$$

where $u_k'(i)$ is the deviation of the zonal wind at day *i* in year *k* from its long-term mean. That is, $u_k'(i) = u_k(i) - \frac{1}{n}\sum_{k=1}^{n} u_k(i)$.

Tables 1 and 2 show the correlations for NCEP/NCAR and CMAM, respectively, between the zonal winds over Vanscoy, between the zonal-mean winds at the Vanscoy latitude and between the two, for the indicated number of days before turnaround. (The MetO record was considered too short to give useful results in this respect.) Values that are statistically significant within 95% confidence bounds are indicated in bold

TABLE 2. As in Table 1, but for 24 years of CMAM model data at the 10-mb pressure level over (50.625°N, 108.75°W). The 20-day points in the first two rows are anomalously high – for the days on either side of these points, the correlations are statistically insignificant.

	30 days	20 days	10 days
Autocorrelation coefficients of zonal winds over (50.625°N, 108.75°W)	0.018	**0.575**	0.088
Correlation coefficients of zonal mean wind at 50.625°N to the zonal winds over (50.625°N, 108.75°W)	0.288	**0.510**	0.389
Autocorrelation coefficients of zonally averaged zonal winds at 50.625°N	**0.520**	**0.550**	**0.524**

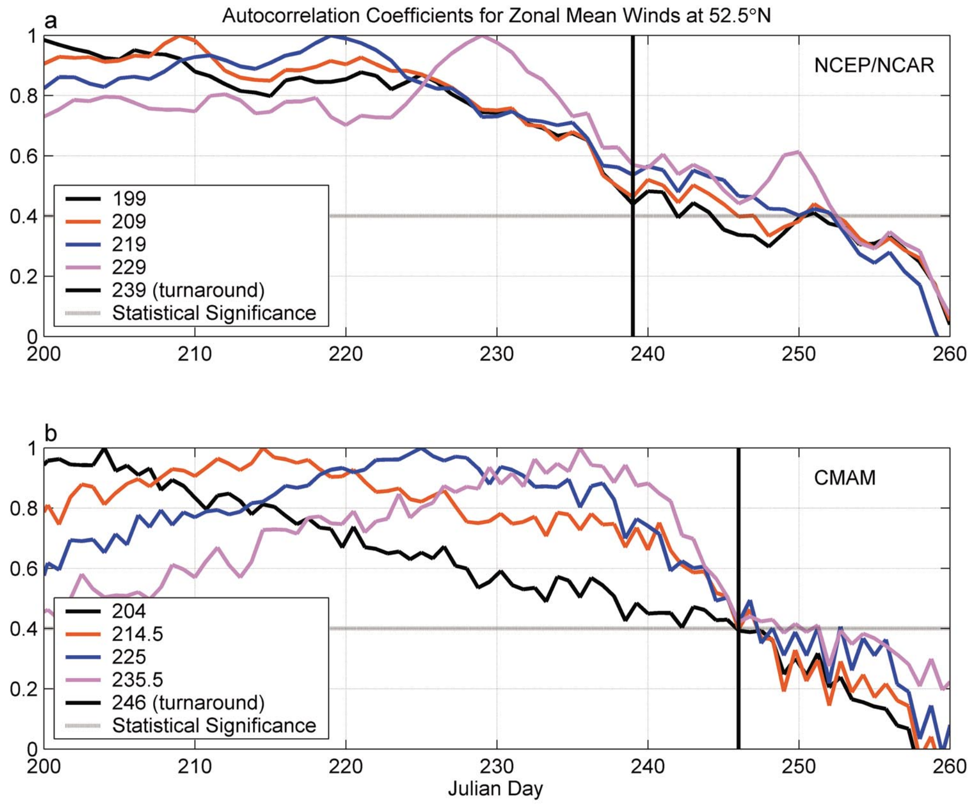

Fig. 9 Autocorrelation coefficients between the 10-mb zonally averaged zonal wind at the start date with previous and future dates: a) NCEP/NCAR Reanalysis, 52.5°N, 1979–2003; and b) the corresponding coefficients from the CMAM simulation. A value above 0.4 is statistically significant for both datasets.

font, taking into account the length of each dataset. The confidence bounds were calculated using Fisher's *z*-Transformation. Both datasets show that there is no significant correlation at 10 mb between the zonal wind velocity over Vanscoy at turnaround and its value 10, 20 or 30 days ahead. However, significant correlations are found for the zonal-mean winds. Thus in what follows, we analyse only the zonal-mean wind.

Figure 9 shows the autocorrelation coefficients for the zonal-mean wind over Vanscoy at 10 mb, using the NCEP/NCAR Reanalysis data in Fig. 9a and the CMAM data in Fig. 9b. The autocorrelations are shown relative to the wind 10, 20, 30 and 40 days ahead of the average turnaround for that dataset. From Fig. 9a, one can see the persistence of high autocorrelations early in the summer for days separated by more than a month. However, before turnaround the correlations drop off drastically, diminishing the predictability of turnaround. Anomaly forecasts 10, 20, 30 and 40 days ahead of turnaround are all of roughly equal value, though the value is only marginal. This is somewhat reminiscent of the high persistence of mid-latitude total ozone anomalies during the summertime, followed by a rapid loss of memory in the fall (Fioletov and Shepherd, 2003), although it is much less drastic. The CMAM data do not fully capture the persistence of high correlations during the summer months, but they do capture the abrupt drop-off of the correlations just before turnaround, with all forecasts being of roughly equal (marginal) value at turnaround (see also Table 2).

Figure 10 shows the complete autocorrelation matrix of the 10-mb zonal-mean winds over Vanscoy for the NCEP/NCAR Reanalysis. Figure 9a is a subset of the rows contained in Fig. 10. From Fig. 10, it is clear that there is a block of time during the early summer when the autocorrelations of the zonal-mean winds are high. These correlations reduce around midsummer and then sharply decline around day 239.

b *A Cautionary Note*

Unrealistically high autocorrelations can be obtained due to temporal inhomogeneities or long-term trends in a dataset. The NCEP/NCAR Reanalysis spans the years from 1948 to the present day, using the same reanalysis data assimilation scheme for all years. However, during this time, there were three well-defined observing regimes (Kistler et al., 2001): between 1948

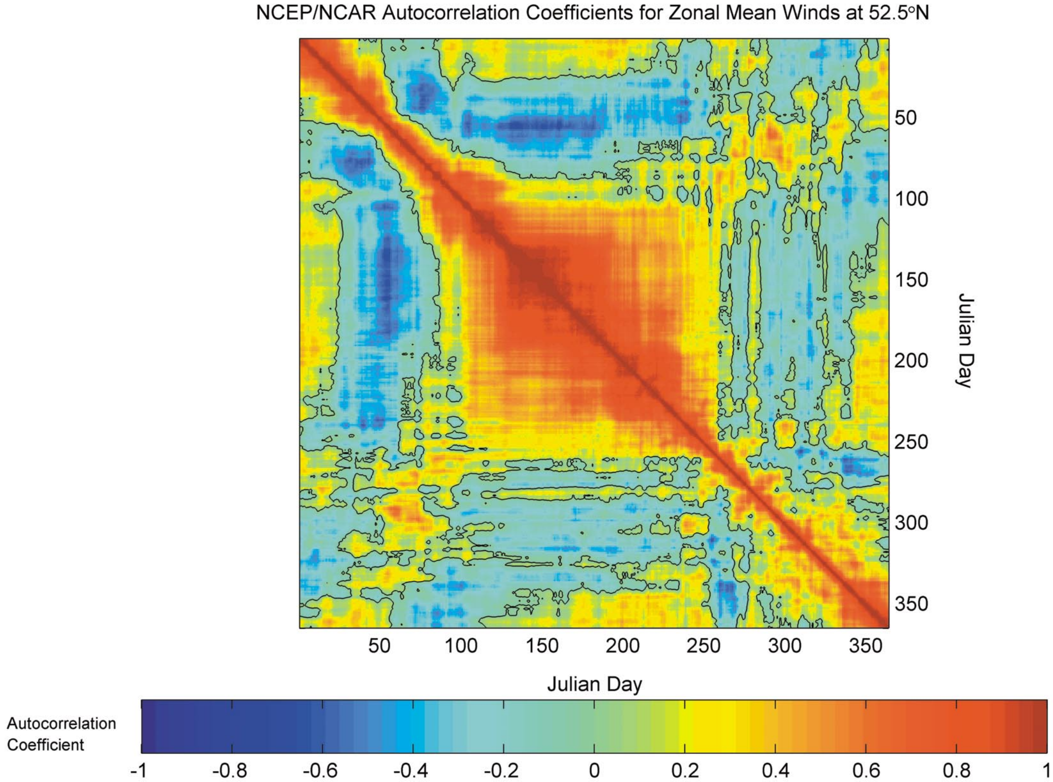

Fig. 10 Autocorrelation coefficients of the 10-mb zonally averaged zonal winds, at 52.5°N, calculated using years 1979–2003 of the NCEP/NCAR Reanalysis data.

and 1957, very few data were input into the assimilation scheme (although the paucity of data was mainly in the southern hemisphere); from 1958 to 1978, upper air observations were available; and from 1979 to the present day, the modern satellite network was used. Any of the shifts from one observing regime to another may cause a temporal inhomogeneity. Figure 11 shows the NCEP/NCAR August mean zonal wind at 10 mb and 52.5°N for the entire dataset. A distinct trend prior to the early 1970s is apparent. Whether real or not, such a trend can introduce spuriously high autocorrelations. Figure 12 illustrates the remarkably strong correlations that result compared with Fig. 10, when just using the period 1948–69.

5 Discussion and conclusions

An initial climatology of the turnaround phenomenon over Vanscoy, Saskatchewan (52°N, 107°W) has been presented, using NCEP/NCAR Reanalysis data, MetO analysis data, and model data from the CMAM. The typical progression of the late summer turnaround through the northern mid-latitude stratosphere has been described. For coincident years, the NCEP/NCAR zonal winds at 10 mb over Vanscoy are, on average, about 2 m s^{-1} more westerly than the MetO winds from midsummer to early fall, and turnaround accordingly happens about six days earlier.

Two different methods of analysing the NCEP/NCAR data yielded similar results for the expected date of turnaround: day 239 or 240, with a standard deviation on the order of one week. Statistical analysis suggests that there is no relation between the length and the date of turnaround, or between the date of turnaround and the occurrence of the peak easterly wind velocity in midsummer. The autocorrelation analysis for zonal-mean winds indicates that, as we approach turnaround, the correlations drop off sharply, whereas during midsummer, the correlations remain high for lags as long as 25 days.

These results have provided us with valuable information: during every year of the 1993–2002 period, an appropriate balloon-launch window has included days 238 to 248 (26 August to 5 September). Crucially, this is true for both observed datasets. Figure 5, however, suggests that a more southerly launch site would allow for more predictability, since the zero contour of zonal mean wind becomes fairly zonally symmetric below about 50°N as it migrates south. This, in fact, is the case, as illustrated in Fig. 13. There is a balloon launching site in Palestine, Texas, (31°N, 95°W) where high predictability of zonally averaged zonal winds persists through turnaround. We have chosen our launch site for scientific reasons: the MANTRA campaign is a Canadian project primarily concerned with mid-latitude stratospheric ozone chemistry. However, this information could be useful for other campaigns.

There is evident variability in the zonal wind in the summer, with an interannual standard deviation of daily data of about 2 m s^{-1}. During the summertime, there is limited planetary-wave propagation into the middle stratosphere, and from the perspective of downward control (Haynes et al., 1991; Shepherd 2002), one therefore expects little variability in winds. However, transient episodes of wave drag in the upper troposphere or lowermost stratosphere, associated with synoptic-scale or with evanescent planetary-scale waves, could induce

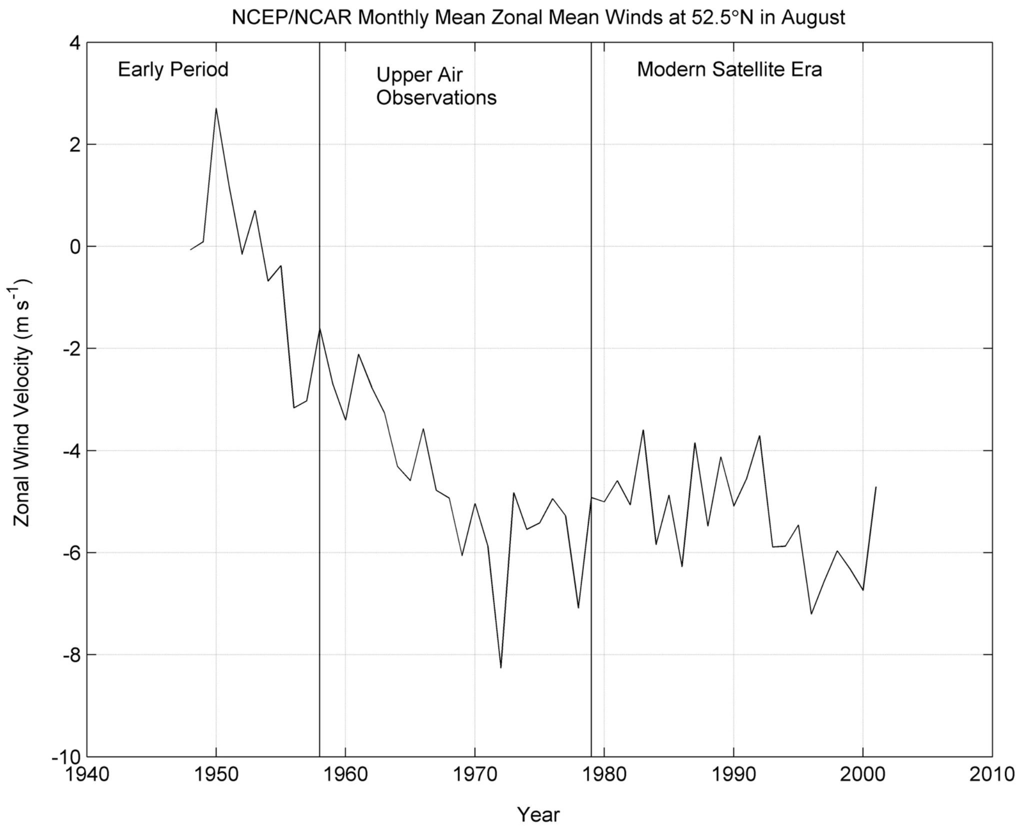

Fig. 11 Time series of the monthly mean zonal mean winds at 10 mb and 52.5°N in August from the entire NCEP/NCAR Reanalysis data (1948–2003). The three observing regimes during this time period are indicated by vertical lines.

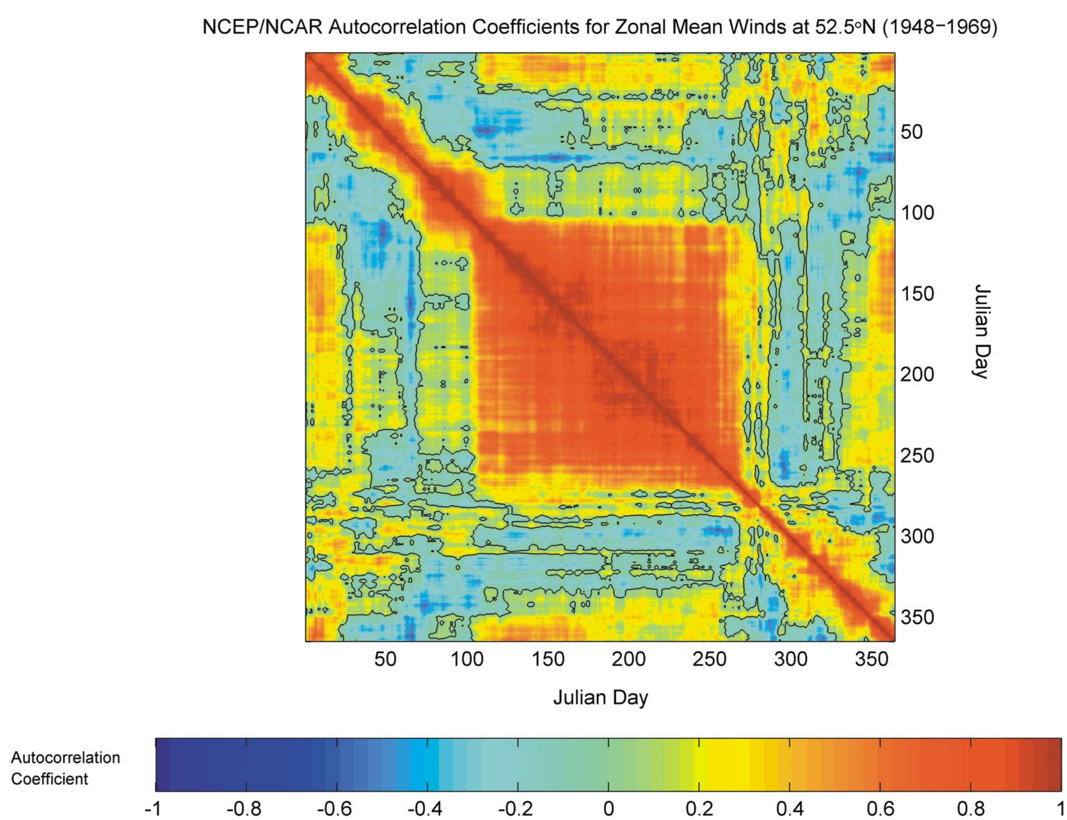

Fig. 12 Autocorrelation coefficients of the 10-mb zonally averaged zonal winds, at 52.5°N, calculated using years 1948–1969 of the NCEP/NCAR Reanalysis data. Note the high autocorrelation coefficients compared with Fig. 10.

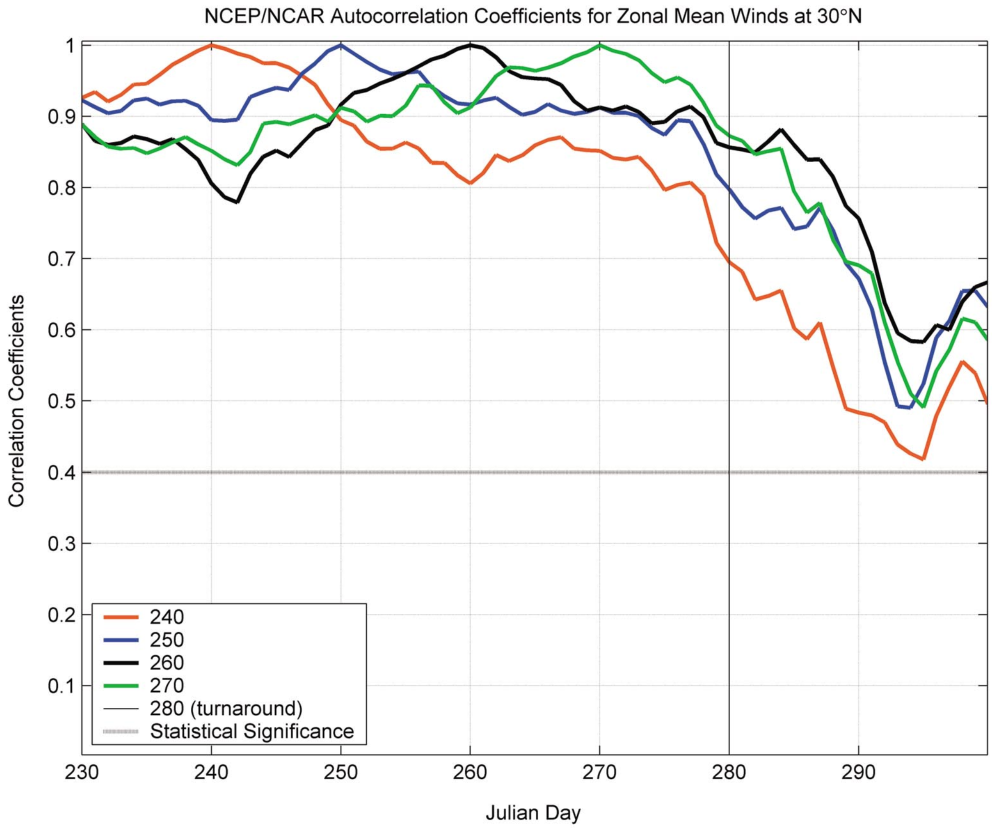

Fig. 13 Autocorrelation coefficients of the 10-mb zonally averaged zonal winds at 30ºN. A value above 0.4 is statistically significant. Note the high correlation coefficient at turnaround, even with winds 40 days before.

circulations extending into the stratosphere which would affect stratospheric temperatures and therefore winds. There is also in situ stratospheric variability associated with the five-day wave (Salby, 1984). The cause of the summertime variability in stratospheric winds merits further investigation.

A particularly striking feature of the autocorrelation plots of zonal mean winds is the sharp decline of the autocorrelations just before turnaround. From a statistical point of view, there is nothing special about turnaround since autocorrelations refer to anomalies. But from a dynamical point of view, zero wind is rather special, because stationary Rossby waves cannot propagate in an easterly zonal flow. Thus, as soon as westerlies appear, Rossby waves can enter the stratosphere and affect its evolution. In this sense, turnaround becomes a strongly non-linear event, with the possibility of increased variability. It may not be a coincidence that turnaround occurs simultaneously throughout the middle and upper stratosphere (Fig. 3). This rapid drop-off of stratospheric memory and its presumed connection with the onset of planetary Rossby-wave propagation into the stratosphere would also be an interesting subject for further analysis, especially given that the drop-off apparently *precedes* turnaround.

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