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Multiple jets observed in the summer Northern Hemisphere troposphere

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Summary. — Daily observations of the Northern Hemisphere zonal mean zonal wind during July show an intermittent formation of multiple tropospheric jet streams. In particular, a tropospheric westerly, or easterly, jet occurs at latitudes greater than 75 °N: it co-exists with the mid-latitude jet and is characterized by variability on synoptic time scale. Two sample years are here considered, July 1996 and July 1985, when prevailing westerly and easterly jets occur at high latitudes, respectively. Analysis is consistent with a picture where the physical mechanism, which creates and maintains the polar jet in the summer troposphere, is the baroclinic instability process acting on a westerly, or easterly, background zonal flow. Due to the synoptic variability, monthly mean maps of the zonal mean zonal wind for July may show different jet patterns as a function of the year, depending on the occurrences (number and duration) of westerly or easterly polar jets within each month considered. The study of the inter-annual variability of the zonal mean zonal wind through the principal component analysis indicates, in fact, that three tropospheric jet stream patterns can be distinguished. Consistency of observations with the available theories on the double-jet formation is provided and the impact of polar jet occurrences on surface temperature field is evaluated.

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1. – Introduction

Several studies, based on observations and/or models, are devoted to the analysis of multiple regimes and low-frequency variability in the zonal mean zonal flow during winter, both for the Northern and Southern Hemisphere. Following the papers of Rossby and Willet [1] and Namias [2], it has been recognized that the jet(s) axis occasionally undergoes a vacillation, so that its position is not always located near the climatological mean. More recently, many authors, following also the paper by Lorenz [3], confirmed these early observations and found a similar behaviour ([4-10], just to mention a few). On the other hand, Hunt [11], following the theoretical analysis of Matsuno [12] and Dickinson [13], suggested that stratosphere-troposphere coupling could induce a similar vacillation. Theoretical motivations, as proposed by Lindzen [14] and discussed in Bordi *et al.* [15, 16], have outlined a possible stratosphere-troposphere interaction through the modification of the baroclinic instability property of an atmosphere without a rigid lid at the tropopause. Thus, it appears that the maintenance of the jet variability may be strongly influenced by complex modifications of baroclinic waves when a coupling between stratosphere and troposphere is considered.

However, there are merely a few papers devoted to the study of the zonally averaged circulation variability during Northern Hemisphere summer [17]. Probably this is because: i) the role of the eddies in generating the main features of the general circulation can be better understood for periods of their maximum activity (*i.e.* during winter); ii) there is interest in investigating the origin of the observed subtropical jet that occurs in winter in both hemispheres or in Southern Hemisphere summer.

Recently, manifestations of anomalous summer weather have increased the research on the atmospheric conditions during summer months in the Northern Hemisphere [17-19]. Thus, analyzing the zonally symmetric circulation variability is an important issue for fully understanding such observed anomalous conditions.

Observations suggest that key features of the climatological zonal mean zonal wind in the summer Northern Hemisphere troposphere are the presence of a westerly jet centred at about 45 °N and a hint of a secondary, less intense, westerly jet in mid-high latitudes. Easterlies, instead, characterize the stratosphere and the tropical region. The question is if the feature of a secondary jet occurring at mid-high latitudes is due to a vacillation of the main jet stream or co-existing double jets occur in the summer troposphere. The central problem is also the underlying physical mechanism that creates and maintains this feature of the general circulation. We address this by means of an observational study based on re-analysis data.

First, analyzing daily data for July, we provide evidences for multiple jets in the Northern Hemisphere troposphere. Two years are considered as an example, July 1996 and July 1985, when prevailing westerly and easterly jets occur at high latitudes, respectively. Then, we analyze the role of synoptic eddies in establishing the observed polar jets and discuss the coherence with recent theories on double-jet formation.

Two general approaches, in fact, have been taken to explain zonal jets observed in the planetary atmospheres: in the first case jets are thought to be generated by the effects of differential rotation on a turbulent fluid [20-23], while in the second case multiple jets may originate from baroclinic instability process through the non-linear interaction between the eddies and the mean flow in an atmosphere subjected to an imposed thermal forcing (see, for example, [24-26]).

Due to the high variability on synoptic time scale of the zonal mean zonal wind, monthly mean maps may show single- or double-jet pattern depending on the occurrences of westerly or easterly jets at mid-high latitudes within the month. These kinds of patterns characterize, in fact, the inter-annual variability and can be distinguished by applying the Principal Component Analysis (PCA) to the monthly zonal wind fields.

Furthermore, we investigate the relationship between the inter-annual variability of the summer Northern Hemisphere Annular Mode (NAM) and that of the zonal wind following Ogi *et al.* [17, 27] argumentations. Recent works [28-31], in fact, suggest that the annular mode variability might be the signature of eddy-mean flow interaction and Ogi *et al.* [17, 27] argue that positive summer NAM index includes representations of tropospheric double-jet streams.

In assessing the issue described above, the present paper is structured as follows. Section **2** describes data and methods of analysis. In sect. **3** the analysis based on daily data is provided for two sample years, while in sect. **4** recent theories on double-jet formation are discussed in relation to the observational evidences. Section **5** shows the main results obtained for the inter-annual variability of the zonal mean zonal wind in July. The final section summarizes the study and outlines future investigations.

2. – Data and methods of analysis

The analysis is based on the ECMWF re-analysis data ERA-40 [32]. Data are available at $2.5^\circ \times 2.5^\circ$ regular latitude/longitude grid from 1000 mb up to 1 mb (23 pressure levels). Daily data for two sample years, July 1996 and July 1985, are used to illustrate the variability on synoptic time scale, while monthly mean data from 1958 to 2002 are used for analyzing the inter-annual variability of the zonal mean zonal wind.

In order to classify jet patterns on monthly basis, PCA is applied to the temporal covariance matrix of the zonal mean zonal wind field from 775 mb up to 100 mb and in the latitude range 30 °N–90 °N: the anomaly field used for computation of the covariance matrix is the deviation from the averaged value over the time record considered.

We compare the resulting behaviour of the first principal component score with the Seasonally Varying Northern Hemisphere Annular Mode (SV-NAM) index proposed by Ogi *et al.* [27]. The authors define the SV-NAM index as the standardized score of the leading principal component of the monthly and zonally averaged geopotential height fields poleward of 40 °N from 1000 mb to 200 mb. The index is based on 45 years (1958–2002) of monthly-mean data from NCEP/NCAR and the time series for each calendar month is available on the web at `http://wwwoa.ees.hokudai.ac.jp/svnam`. Following Ogi *et al.* [27] we compute the NAM index time series for July using ERA-40 geopotential data, finding almost the same results (correlation coefficient 0.92).

Tropopause pressure data here used has been retrieved from the NCEP/NCAR re-analysis data set, since in ERA-40 re-analysis they are missing.

3. – Variability on synoptic time scale

The climatology of the zonal mean zonal wind, computed over the period 1958–2002, for July (fig. 1a) shows a main westerly jet at about 45 °N in the Northern Hemisphere with maximum intensity at 200 mb and a hint of a secondary jet around 70 °N reaching maximum value at 250–300 mb. Easterlies dominate the tropical regions from the surface up to the stratosphere, where they are particularly strong reaching polar latitudes. Note that the pattern is the same when other summer months are considered, say June or August. Now the question is whether such a feature of secondary jet is related to a vacillation of the main jet stream axis or co-existing double jets occur in the summer troposphere. To shed light on this item, we analyse the time variability for two sample years, July 1996 and July 1985, whose monthly mean maps show a double-jet and a single-jet pattern, respectively (see fig. 1b–c).

3·1. *Daily variability of the zonal wind.* – Hovmoeller diagrams of the zonal mean zonal wind at tropopause pressure level are shown in fig. 2 for the two years considered. It can be noted that both years are characterized by a high variability (intensity and meridional wandering) on synoptic time scale affecting both the main jet and the secondary one:

i) July 1996 shows multiple jets in the first half of the time section with westerly jet streams at 45 °N and 85 °N. During the following days, a secondary jet occurs near 75 °N, occasionally accompanied by easterlies at high latitudes.

ii) July 1985 is characterized by a strong westerly jet around 40°–45 °N and strong easterlies at mid-high latitudes from day 10 to 20. Days of multiple westerly jets are present also in this case but they are less frequent and often flanked by easterly winds.

Note that in both cases the main jet axis remains located around 45 °N with a low-frequency variability of a few degrees in latitude. Thus, the different variability on

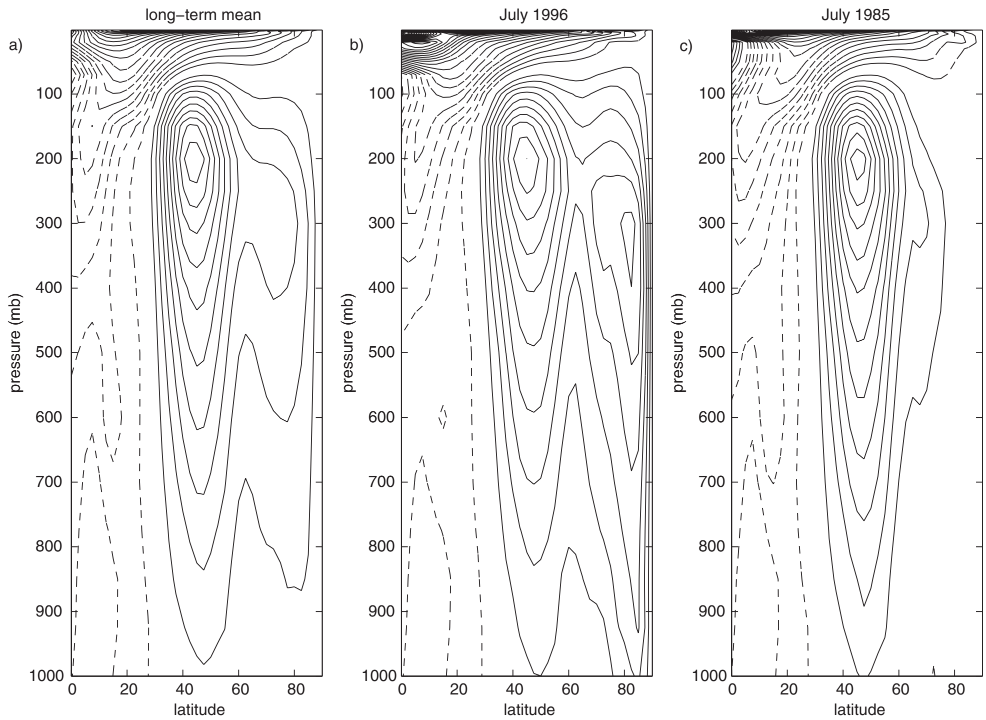

Fig. 1. – Latitude-height (pressure) cross-section of the zonal mean zonal wind: a) long-term mean over the period 1958-2002 for July, b) July 1985 and c) July 1996. Contour interval is $2\,\mathrm{ms}^{-1}$ and zero line is excluded; dashed lines denote negative values.

synoptic time scale between the two years explains the differences in the monthly mean maps shown in fig. 1b, c, suggesting that the dynamics of the double-jet in the summer troposphere is related to the crucial role played by synoptic eddies.

An inspection of the time evolution of the zonal mean zonal wind in the latitude-height (pressure) cross-section for the two years (see figs. 3a–c) deserves further considerations.

During 1996, the amplification of westerly polar jet is accompanied by a lowering of the tropopause height (see thick line during days 3–6, 9–12), while easterly polar jet is associated to a raising tropopause height (days 30–31). At mid-high latitudes easterlies are confined in the stratosphere and the dynamics of the mid-latitude jet and that of the polar one seem to be not related. Moreover, in agreement with the baroclinic life cycle, in conjunction with the maximum strength of the polar jet there is an enhancement of the vertical wind shear, while the contrary occurs during its decay.

During 1985, instead, there is a period of about 10 days (days 10–20) when an easterly jet occurs at high latitudes: it originates from an easterly background flow, which favours an intrusion of stratospheric easterly wind into the tropospheric layers, hinting at the existence of a radiative equilibrium over all the vertical column.

3˙2. *Temperature fields and eddy heat fluxes*. – Hovmoeller diagram of eddy temperature field, zonal wave number 2 at 850 mb at 80 °N (figs. 4a, b), shows westerly propagation during periods of westerly polar jets, while the propagation is easterly when an easterly jet is present. On the other hand, power spectra of meridional eddy heat fluxes ($v'T'$) at 850 mb (fig. 5) suggest that they are particularly active during days preceding

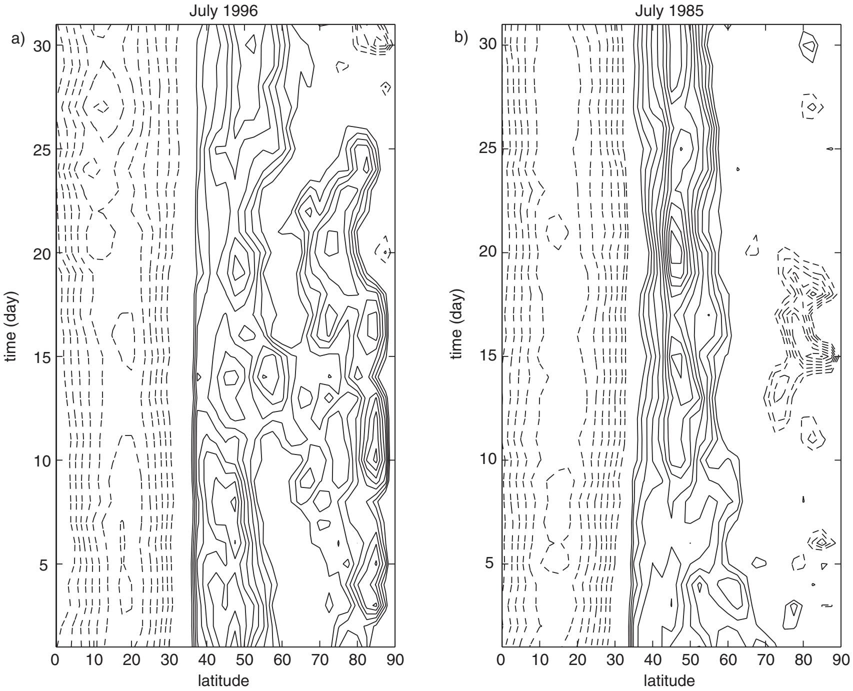

Fig. 2. – Latitude-time (Hovmoeller) diagrams of the zonal mean zonal wind at the tropopause pressure level for: a) July 1996 and b) July 1985. Unit is ms^{-1}, contour interval is $2\,ms^{-1}$ and zero line is excluded. Solid lines denote westerlies greater than $10\,ms^{-1}$ and dashed lines easterlies.

the maximum amplification of the westerly/easterly polar jet: peaks are noticeable at zonal wave numbers 2 to 5 poleward of 75 °N. This behaviour supports the hypothesis that meridional heat fluxes induced by transient eddies, and thus the baroclinic instability, play a key role in establishing the secondary jet in the polar region.

Furthermore, an inspection of daily standardized temperature anomaly field (deviation from daily climatological mean divided by daily standard deviation) at 850 mb for the two years (figs. 6a, b) shows that occurrences of westerly polar jets are associated with negative anomalies at high latitudes, while positive anomalies characterize periods when easterlies dominate the polar region. Prevailing (weak) positive temperature anomalies at 50°–60 °N are noticeable during years characterized by double-jet like 1996. However, only limited regions close to the pole show temperature anomalies greater than 1 standard deviation (thick lines in the figures), suggesting that the occurrences of double-jet do not have an impact on temperature anomaly field which is not statistically significant (*i.e.* such occurrences are not unusual but rather frequent events).

Furthermore, it can be noted that while in conjunction with an intensification of the secondary jet the polar region becomes colder (see fig. 6a), before (or after) such an event the temperature anomaly is still negative but less intense. Thus, it appears that, on the synoptic time scale, a feedback mechanism tries to modify the meridional temperature gradient. A plausible physical mechanism able to do this is the baroclinic instability through its eddy-induced heat and momentum fluxes. In the following section we discuss the consistency of such features with the current theories on double-jet formation.

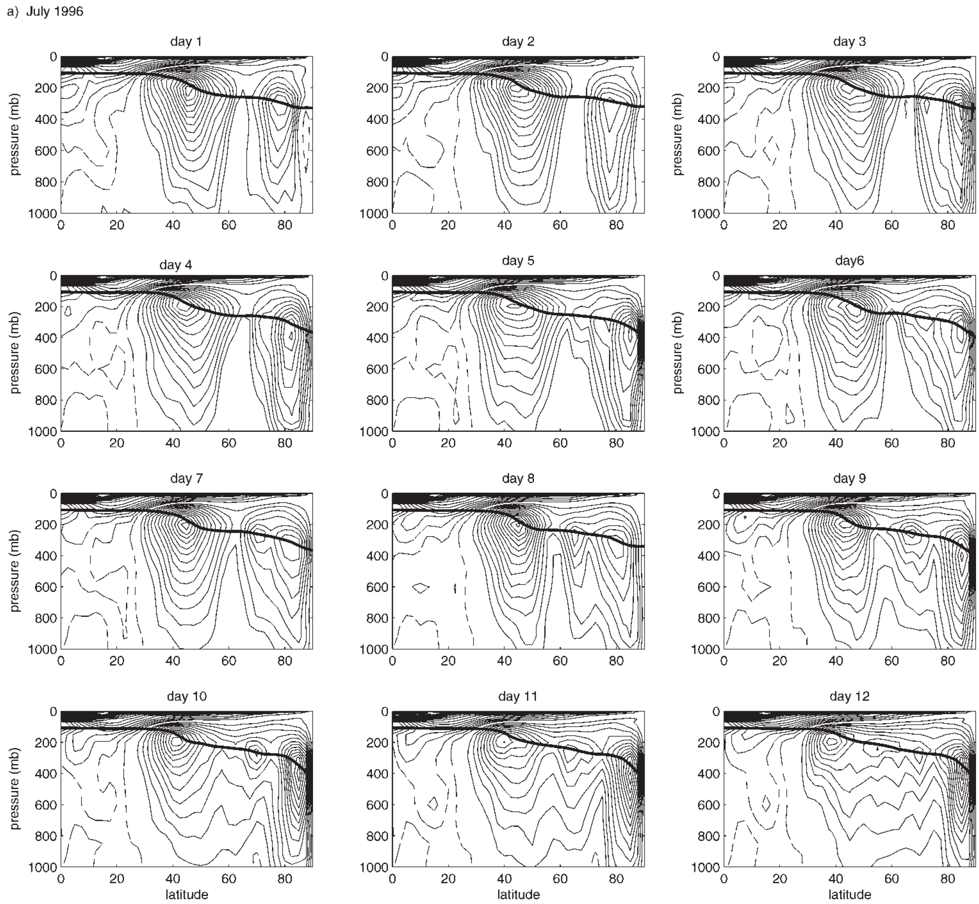

Fig. 3. – Latitude-height (pressure) cross-section of daily zonal mean zonal wind for: a)–b) July 1996 days 1–12, 25–31, and c) July 1985 days 10–21. Contour interval is $2\,\mathrm{ms}^{-1}$ and zero line is excluded; dashed lines denote negative values and thick line marks the tropopause pressure.

4. – Theories on double-jet formation

The origin of zonal jets in the planetary atmospheres, including the Earth's one, has been the subject of many theoretical and experimental studies. Two competing theories emerge to be plausible for explaining jets formation: in the first case jets are generated in a turbulent fluid due to the effects of differential rotation, known as the "β-effect", while in the second case multiple jets may originate from baroclinic instability process through the non-linear interaction between the eddies and the mean flow in an atmosphere subjected to an imposed thermal forcing.

In the last decades, it has been widely accepted that, as in two-dimensional turbulence, the barotropic component of eddy kinetic energy cascades from the length scales of baroclinic instability to larger scales in an inverse energy cascade mediated by non-linear eddy-eddy interactions. Unless dissipation or the limited size of the planet arrest the inverse cascade at a smaller scale, the energy continues to cascade up and accumulates near the "Rhines scale", where it is channelled into zonal jets and Rossby waves [20-22, 33, 34]. Thus, the two crucial length scales are that of the linearly most unstable

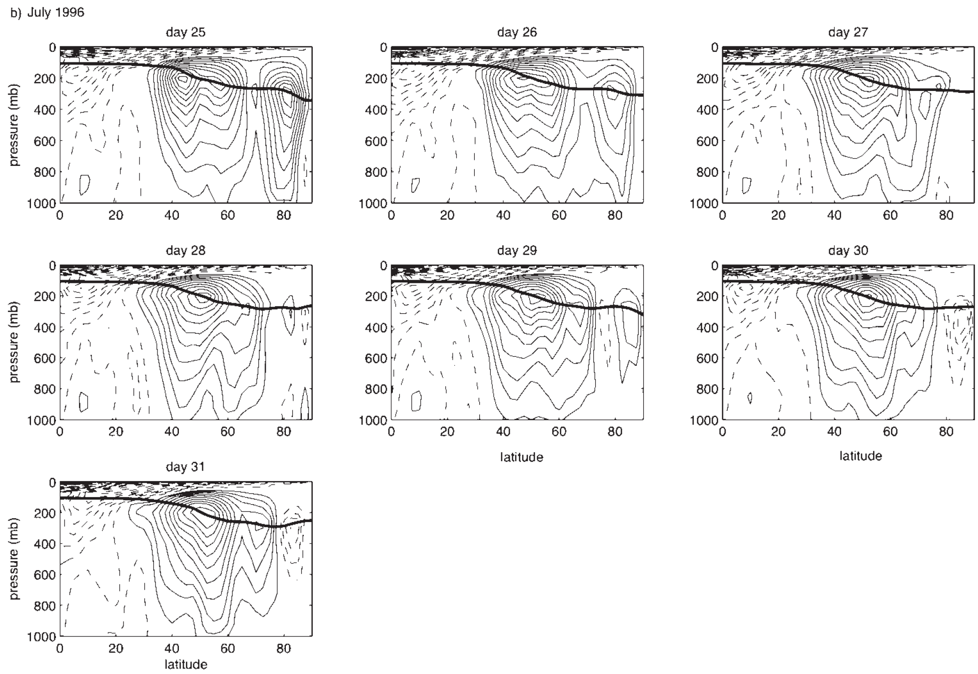

Fig. 3. – *Continued.*

baroclinic waves, *i.e.* the Rossby radius of deformation L_{R}, and the Rhines scale L_β, which in its original definition is obtained by equating the r.m.s. velocity U to the phase speed of the Rossby wave. In Earth's atmosphere these two length scales seem to be of the same order of magnitude and there is no evidence for an inverse energy cascade beyond the scale of the most linearly unstable baroclinic waves (see [35,36] and references therein). It seems, in fact, that the baroclinic eddies, interacting with the mean flow, inhibit non-linear eddy-eddy interactions that would engender an inverse energy cascade.

Recently several works have been devoted to understand the role of baroclinic instability in the generation of zonal jets [24-26, 37, 40]. These efforts are based on primitive equations forced by a Newtonian cooling or two-layer quasi-geostrophic models that take into account the non-linear interaction between the disturbance and the mean flow. In the latter case the non-linear baroclinic interaction gives a zonal mean correction to the basic flow that provides the double-jet structure as observations suggest.

Note that for the cases here presented the secondary jet forms at high latitudes where the β-effect is very weak and tends to zero approaching the pole (thus, we should expect instead an f-effect). However, when a westerly polar jet occurs, if we compute the Rhines scale, we find that it is comparable to the Rossby radius. On the other hand, when an easterly polar jet occurs the Rhines scale meaning is partially lost, while models of baroclinic instability, like Eady model [39], hold also for an easterly basic state. Furthermore, consistent with the recent theories on non-linear baroclinic adjustment, re-analysis data suggest that eddy heat fluxes have a role in the formation of the polar jet: meridional eddy heat fluxes have their maximum activity some days before the amplification of the secondary westerly/easterly jet as occurs during a baroclinic life cycle. The tropopause pressure at high latitudes drops for a few millibars when the baroclinic disturbances

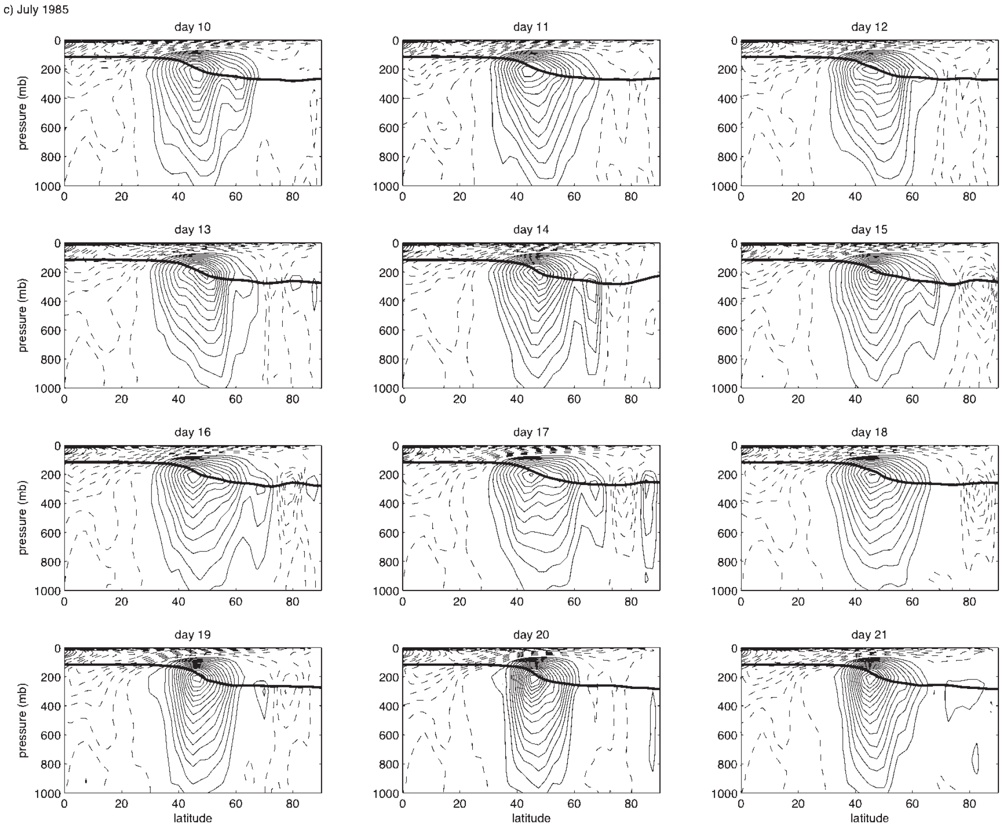

Fig. 3. – *Continued.*

grow and the tropopause height re-adjusts itself to higher pressure levels when the eddy activity dies out.

Finally, about the role of the stratosphere, it seems that during summer, at variance with winter when a westerly stratospheric polar jet favours the vertical propagation of Rossby waves leading to a troposphere-stratosphere interaction, the dynamics is confined in the troposphere and stratospheric easterlies provide a modification of the baroclinic instability property as discussed in Bordi *et al.* [15]. A clear link between stratosphere and troposphere is visible only when a strong easterly polar jet occurs. In such a case it seems that an intrusion of stratospheric easterlies into the troposphere is allowed by an easterly background zonal flow previously generated in the middle troposphere by the eddy activity.

5. – Variability on inter-annual time scale

In order to classify the jet stream patterns occurring on monthly basis, the PCA is applied to the zonal mean zonal wind anomaly.

5˙1. *Jet stream patterns.* – The analysis is restricted to the region where the climatological zonal wind map shows prevailing westerlies, *i.e.* 30 °N to 90 °N and 100 mb to

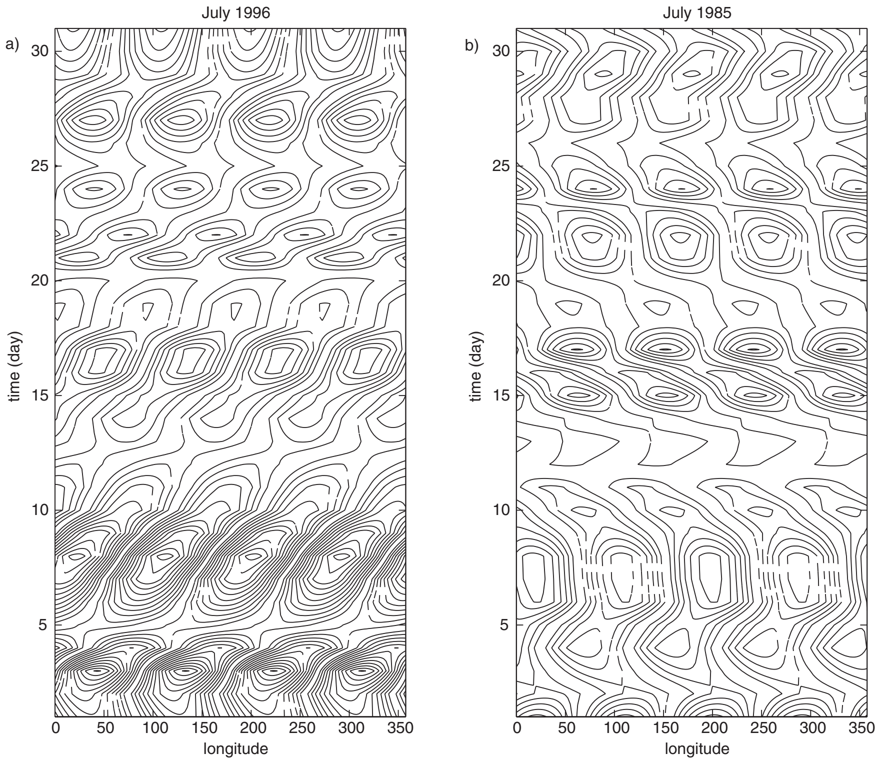

Fig. 4. – Longitude-time (Hovmoeller) diagrams of eddy temperature, zonal wave number 2, at 850 mb at 80 °N for: July 1996 (a) and July 1985 (b). Contour interval is 0.5 K and zero line is excluded; dashed lines denote negative values.

775 mb. Since the high-latitudes jet seems to be better captured by the first PC score computed without weighting the monthly data by the square root of the cosine of latitude, we decide to proceed in our analysis neglecting the equal area adjustment. Thus, the first PC score so constructed represents our indicator for selecting years when a secondary westerly jet occurs at high latitudes.

Figure 7 shows the meridional structure of the first two loadings and the time behaviour of the corresponding standardized principal component scores. It can be noted that the first loading, which explains 41.7% of the total variance, has maximum positive values around 80 °N, while values close to zero occur in mid-low latitudes. Note that the time mean already shows a signature of the double-jet feature (this complicates the classification of the jet patterns). Positive peaks in the PC-1 time series (especially those with values > 1) denote years when a secondary westerly jet stream occurs at high latitudes, while negative peaks characterize those years when such feature is notably reduced. In particular, we found that a few negative peaks (PC-1 < -1) refer to years when only the main jet stream occurs (see table I for details).

The second loading, which explains 19.8% of the total variance, shows positive values in mid-high latitudes with maximum around 65 °N; positive peaks with PC-2 > 1 (excluding years 1989 and 1999 already considered in the analysis of PC-1) select years when an intense secondary jet stream occurs at such latitudes.

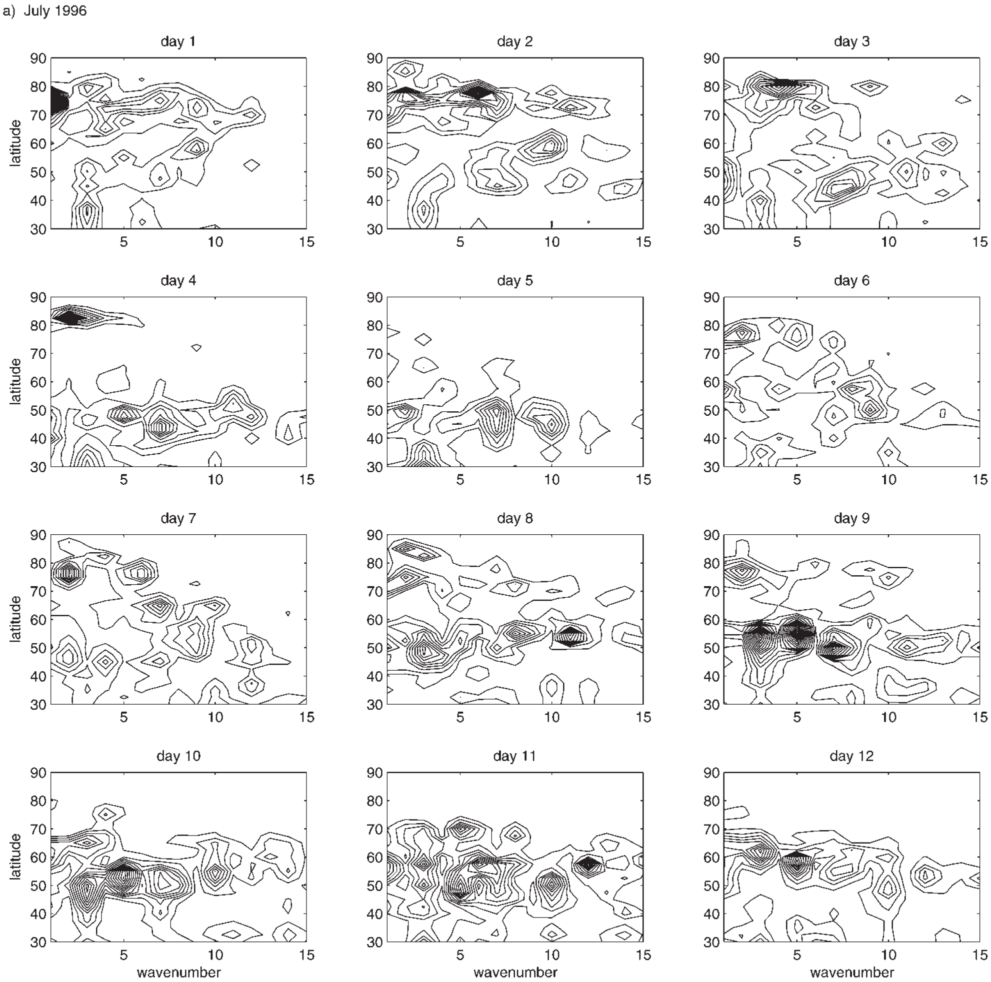

Fig. 5. – Daily power spectra of the meridional eddy heat fluxes ($v'T'$) at 850 mb as a function of the zonal wave number and latitude: a)–b) July 1996 days 1–12, 25–31, and c) July 1985 days 10–21. Unit is $\mathrm{m^2\,s^{-2}\,K^2}$, contour interval is $2 \times 10^3\ \mathrm{m^2\,s^{-2}\,K^2}$ and zero line is excluded.

Summarizing, three tropospheric jet stream patterns can be distinguished, characterizing the monthly mean zonal wind variability during July:

i) A main jet at about 45 °N co-exists with a secondary jet at high latitudes (75°–85 °N).

ii) A main jet at about 45 °N co-exists with a secondary jet at mid-high latitudes (60°–75 °N).

iii) No remarkable secondary jet but only a weak bulge of the main jet (or easterlies) occurs at mid-high latitudes.

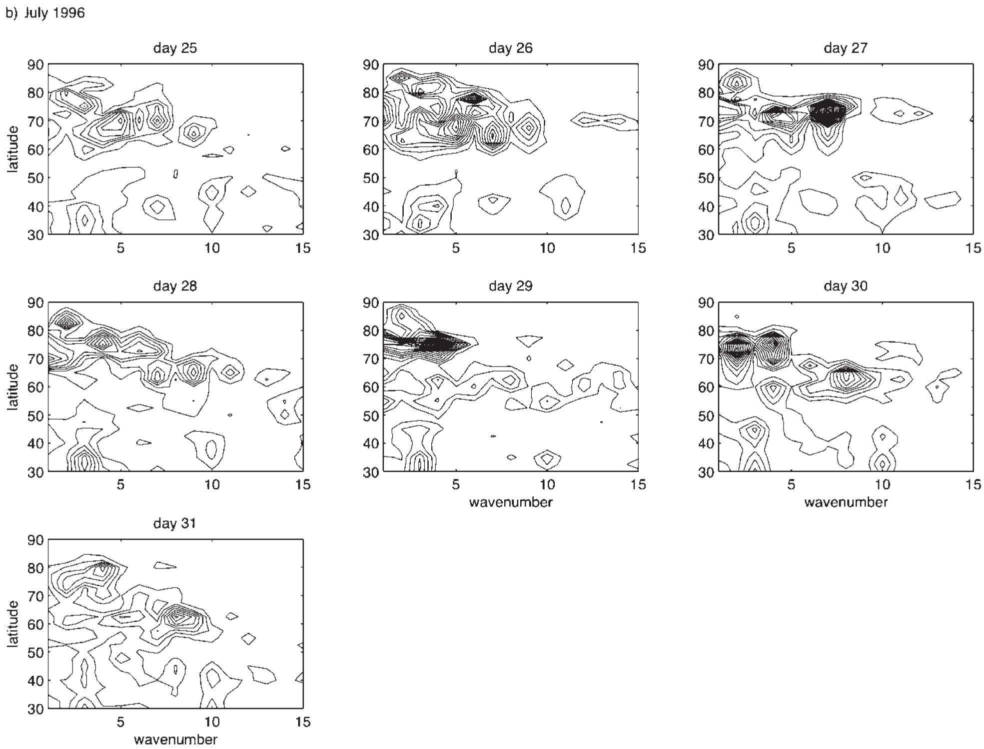

Fig. 5. – *Continued.*

To illustrate these three patterns, figs. 8a-i show the monthly zonal mean zonal wind for sample years, selected from PC-1 and PC-2 time series. Thick line marks the tropopause pressure.

Figures 8a–c clearly reveal a secondary jet at high latitudes, which is less intense (maximum intensity of 10–12 ms^{-1} at 300 mb) compared to the main jet (maximum intensity of 18–20 ms^{-1} at 200–250 mb). Note that weak westerly winds characterize the troposphere around 60 °N leading to a clear separation between the two jet streams. Cases shown in figs. 8d-f display a bulge of the main jet stream between 60°–70 °N (maximum intensity of about 8–10 ms^{-1} at 250–300 mb), which is still at 45 °N with maximum intensity very close to the previous cases. Finally, figs. 8g-i show single jet streams in the troposphere at 45 °N (maximum intensity of 20 ms^{-1} at 200 mb); a weak bulge (about 4–6 ms^{-1}) of the main jet is also noticeable northward of 60 °N in all cases. During July 1995 easterly winds characterize the troposphere poleward of 80 °N.

Note that, in the polar region, the dynamical tropopause for double-jet patterns appears to be lower compared to single-jet cases. This is confirmed by the NCEP/NCAR data on tropopause pressure: positive tropopause pressure (zonally averaged) anomalies poleward of 80 °N, ranging from 10 to 30 mb, characterize years with double jet, while negative anomalies of the same order of magnitude occur for single-jet cases. We find that correlation coefficients between tropopause pressure anomaly time series and PC-1 score are greater than 0.7 for latitudes greater than 80 °N. Following the theoretical approach proposed by Lindzen [14] on tropopause height and baroclinic adjustment, this might suggest that during double-jet years the atmosphere is more baroclinically unstable with respect to years with single jet.

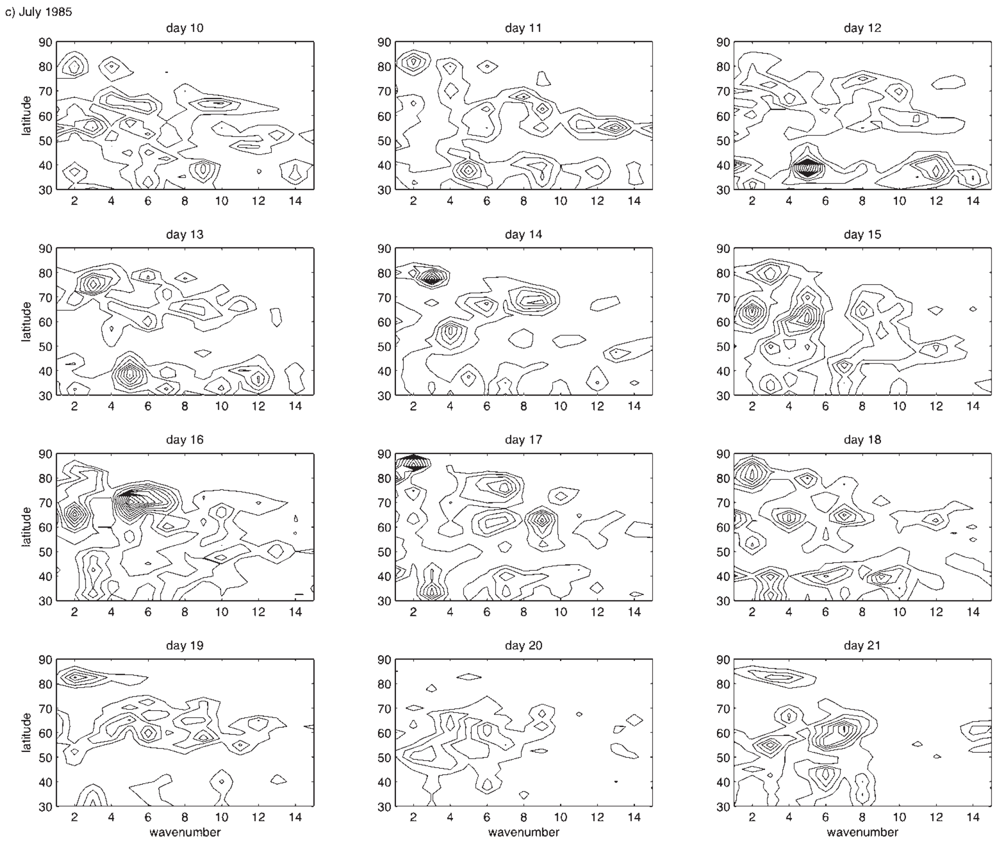

Fig. 5. – *Continued.*

5˙2. *Double-jet and annular mode*. – Recently, Ogi *et al.* [17,27] found that, in positive phases of the summer NAM, a double-jet structure appears in the upper troposphere. Thus, we compare the PC-1 time series shown in fig. 7b with the NAM index for July computed using ERA-40 data, following Ogi *et al.* [27] method (see fig. 9). An inspection of fig. 9 suggests that there is a general correspondence between the positive NAM phase and positive values of PC-1 (that is, double-jet occurrence): the years selected before as double-jet patterns are characterized by large positive values of NAM with the exception of July 1973 when the index is only 0.7. However, there are years when, even if a strong secondary jet occurs at high latitudes (see table I), the NAM index is negative or close to zero (say July 1962, 1972, 1990). On the other hand, years with single-jet structure are characterized by negative NAM index.

For the years when the above discrepancies occur, an inspection of geopotential anomaly fields (both from ERA-40 and NCEP/NCAR) shows that usually a particularly strong negative anomaly of the geopotential height in the polar region is associated with a secondary jet at high latitudes. However, a negative geopotential anomaly does not imply that a secondary jet occurs at high latitudes; in fact, July 1993 and 1998 are characterized by a weak positive geopotential anomaly.

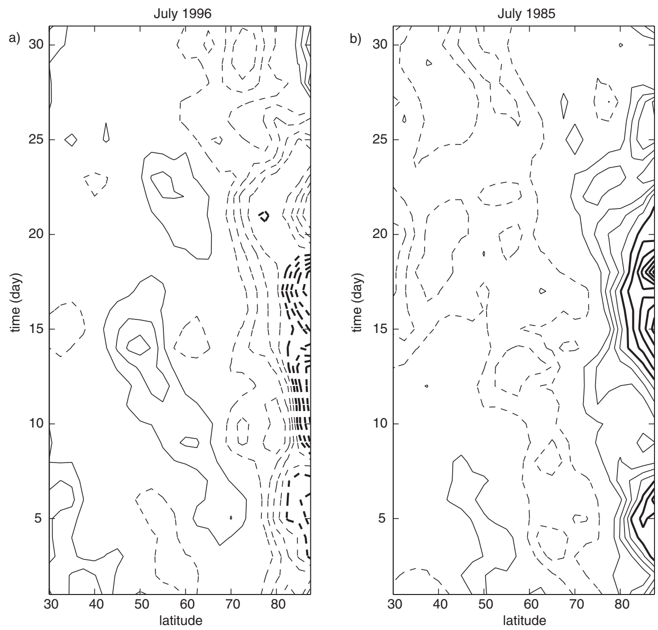

Fig. 6. – Latitude-time (Hovmoeller) diagrams of standardized temperature anomaly at 850 mb for: a) July 1996, b) July 1985. Unit is dimensionless, contour interval is 0.2 and zero line is excluded. Dashed lines denote negative values, while thick lines temperature anomalies greater than 1 standard deviation.

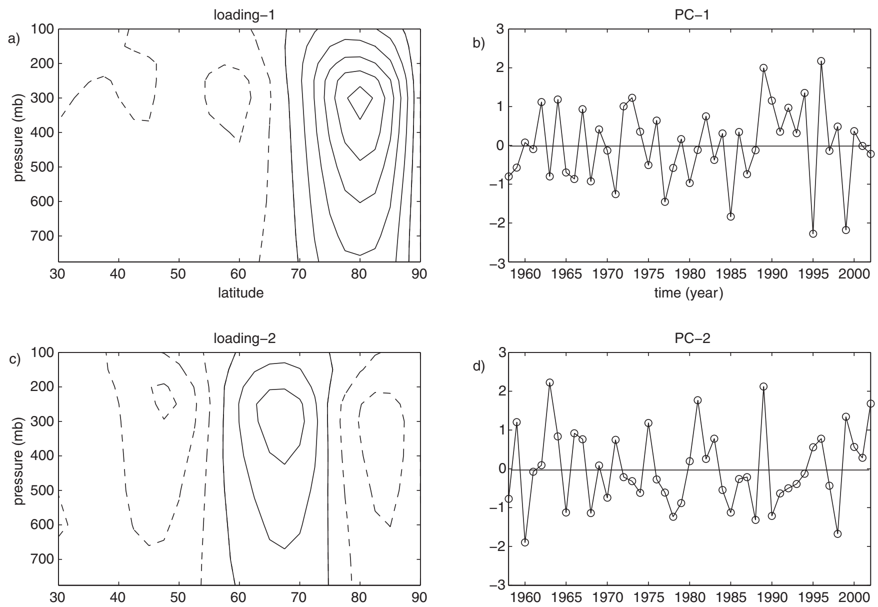

Fig. 7. – PCA: First two loadings and corresponding standardized PC scores of the zonal mean zonal wind for July from 100 mb down to 775 mb and in the latitude band 30 °N–90 °N. Unit in a) and c) is ms^{-1}; contour interval is $0.5\,ms^{-1}$, zero line is excluded and dashed lines denote negative values.

TABLE I. – *Classification of the zonal mean zonal wind patterns based on PC-1 and PC-2 scores of the zonal wind anomaly (see text).*

Year	Secondary jet at high latitudes (PC-1 > 1)	Single jet (PC-1 < −1)	Secondary jet at mid-high latitudes (PC-2 > 1)	Secondary jet: Latitude position and intensity
1958				70 °N 6 ms^{-1}
1959			*	62 °N 9 ms^{-1}
1960				80 °N 7 ms^{-1}
1961				75 °N 7 ms^{-1}
1962	*			75 °N 11 ms^{-1}
1963			*	68 °N 10 ms^{-1}
1964	*			75 °N 10 ms^{-1}
1965				75°-80° 5 ms^{-1}
1966				82 °N 4 ms^{-1}
1967	*			75 °N 10 ms^{-1}
1968				65 °N 6 ms^{-1}, 82 °N 5 ms^{-1}
1969				78 °N 9 ms^{-1}
1970				80 °N 8 ms^{-1}
1971				65 °N 8 ms^{-1}
1972	*			80 °N 10 ms^{-1}
1973	*			75 °N 11 ms^{-1}
1974				78 °N 8 ms^{-1}
1975			*	68 °N 10 ms^{-1}
1976				65 °N 8 ms^{-1} Extends poleward
1977		*		Single jet
1978				80 °N 6 ms^{-1}
1979				80 °N 9 ms^{-1}
1980				65 °N 8 ms^{-1}
1981			*	65 °N 10 ms^{-1}
1982				80 °N 9 ms^{-1}
1983				75 °N 7 ms^{-1}
1984				82 °N 8 ms^{-1}

TABLE I. – *Continued.*

Year	Secondary jet at high latitudes (PC-1 > 1)	Single jet (PC-1 < −1)	Secondary jet at mid-high latitudes (PC-2 > 1)	Secondary jet: Latitude position and intensity
1985		*		Single jet
1986				70 °N 8 ms^{-1} 82 °N 8 ms^{-1}
1987				72 °N 6 ms^{-1}
1988				75 °N 7 ms^{-1}
1989	*			80 °N 13 ms^{-1}
1990	*			82 °N 10 ms^{-1}
1991				75 °N 9 ms^{-1}
1992	*			78 °N 10 ms^{-1}
1993				75 °N 9 ms^{-1}
1994	*			78 °N 12 ms^{-1}
1995		*		65 °N 7 ms^{-1} easterlies > 80 °N
1996	*			82 °N 12 ms^{-1}
1997				72 °N 8 ms^{-1}
1998				80 °N 9 ms^{-1}
1999		*		Easterlies > 80 °N
2000				72 °N 10 ms^{-1}
2001				75 °N 8 ms^{-1}
2002			*	70 °N 9 ms^{-1}

In summarizing, we find results to be in agreement with Ogi *et al.* [27], *i.e.* the occurrence of a double-jet pattern in summer months appears to be related to a negative geopotential height anomaly at high latitudes and associated with a positive (intense) phase of the annular mode. Discrepancies found for July 1993 and 1998 suggest, however, that the double-jet formation is not merely related to the variability of the annular mode on monthly basis since the physical mechanisms leading to the observed inter-annual variability of the zonal wind occur on the synoptic time scale.

6. – Conclusions

The paper provides an observational analysis of the variability of the zonally averaged circulation during July in the Northern Hemisphere based on ERA-40 data. In particular,

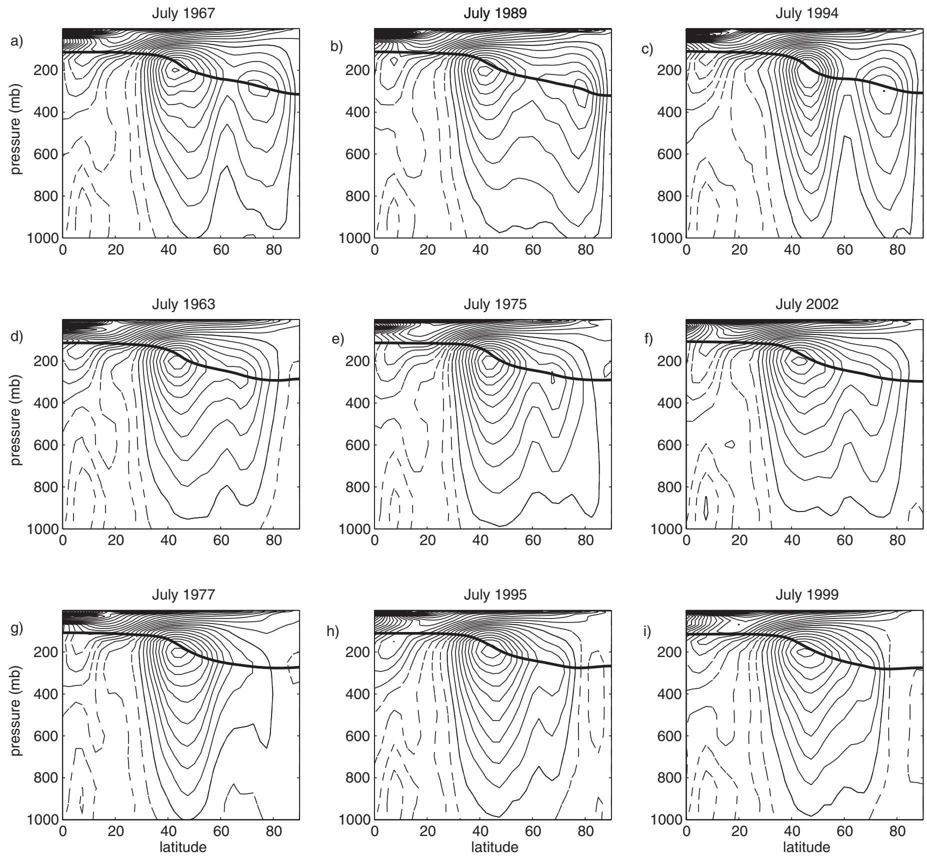

Fig. 8. – Monthly zonal mean zonal wind for sample years characterized by a secondary jet at high latitudes (a–c), by a secondary jet at mid-latitudes (d–f) and by a single jet (g–i). Contour interval is $2\,\mathrm{ms}^{-1}$ and zero line is excluded; dashed lines denote negative values. Thick line is the tropopause pressure.

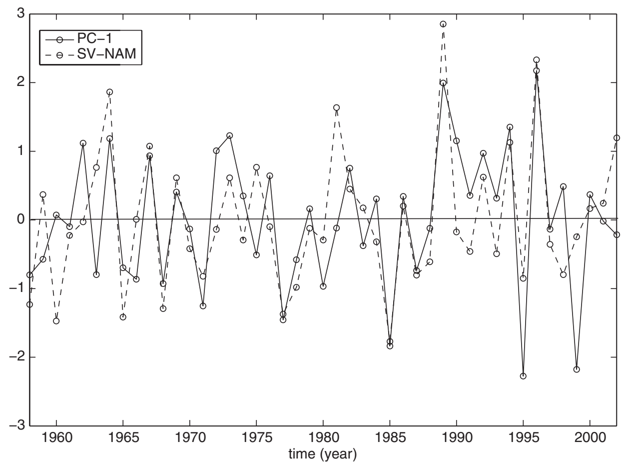

Fig. 9. – Time behaviour of PC-1 shown in fig. 7b (solid line) and the NAM index (dashed line). Data are ERA-40 from 1958 to 2002.

analysis of daily data reveals the existence of multiple jet streams in the troposphere and suggests that the different zonal wind patterns observed on monthly basis are strictly related to the synoptic variability. There is evidence for typical features of the baroclinic instability process, which seems to be the physical mechanism that creates and maintains the westerly/easterly polar jet in the summer troposphere of the Northern Hemisphere. This result is consistent with recent investigations on the baroclinic adjustment of non-linear models and with results obtained from idealized experiments with a global circulation model (PUMA) [37].

Due to the high variability on synoptic time scale, monthly mean maps of the zonal mean zonal wind may show different jet patterns as a function of the year, depending on the occurrences (number and duration) of westerly or easterly polar jets within each month considered. In fact, the study of the inter-annual variability of the zonal wind by PCA indicates three tropospheric jet stream patterns linked with the main jet near 45 °N: i) a secondary jet at high latitudes, ii) a secondary jet at mid-high latitudes, iii) no remarkable secondary jet.

Further effort is required to design and analyze experiments with a simplified forced general circulation model, where the stratosphere is characterized by easterlies and only the effects of the eddies are considered. In addition, from a theoretical point of view, the genesis of multiple jets in a non-linear baroclinic environment should be studied following Charney's approach [40], in order to isolate the effective role played by eddy heat fluxes alone. These research topics are aims of future work.

* * *

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