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P1.36 An Extreme Case of Atmospheric Blocking Over Western Europe

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1. INTRODUCTION

The subject of atmospheric blocking has enjoyed an increasing amount of attention over the past few decades. Perhaps the first major study of blocking flows occurred in 1950, when Rex analyzed and produced one of the first short-term Northern Hemisphere climatologies on blocking anticyclones and their associated flows. In his study, Rex showed that blocking patterns were intimately related to strong surface anticyclones. Rex (1950a&b) also shows that atmospheric blocking may have climatological impacts in that during the events, surface temperatures and amount of sunlight (i.e. less cloud cover) tend to be above normal, while precipitation tends to be lower than normal.

Other research studies concerned with atmospheric blocking have included the study of the temporal duration, strength and regional effects (both upstream and downstream) of the episodes (e.g. Austin 1980; Colucci 1985; Lupo and Smith 1995a&b; Wiedenmann et al. 2002; Burkhardt and Lupo 2005; Galarneau et. al. 2008). It has been shown through various studies that prolonged or episodic blocking over the course of a season can impact the climatological character of the region in which the event occurs for one to two seasons following the event (Rex 1950a&b; Green 1977; Lupo & Bosart 1999).

Over the period of June – August 2003, the western extent of the European continent experienced a heat wave that killed tens of thousands of individuals. This heat wave was induced by an extreme case of atmospheric blocking off the western coast of the continent. All major countries in Europe felt the effects of the heat, however, France suffered the highest fatality rate at around 14,802 individual (Kovats et al. 2004).

In France, surface temperatures reached near-record levels in the final weeks of July. As temperatures continued to rise (and then remained constant), the rates of death mirrored this rise. From about 03 August 2003 to 13 August 2003 the maximum surface temperature peaked and then hovered near 37°C. During this same period, daily minimum temperatures hovered around 20°C. For France, this extended period of heat represented the most extreme heat wave (max., min., and avg. temperature as well as duration) in 53 years (Pirard et al. 2005).

2. CASE STUDY OBJECTIVES

The purpose of this study is to further the understanding of atmospheric blocking flows occurring as 500-hPa positive height anomalies. Prolonged or episodic atmospheric blocking can impact the climatological character of the region in which the blocking occurs for one to two seasons following the event. Moreover, these events can induce heat waves and deprive regions of regular rainfall, affecting the inhabitants of said regions negatively.

Specifically, this study will address how certain diagnostics may be used to diagnose blocking onset and decay, as well as the dynamics of the period of time in between (which will be referred to as the block itself). Of particular note in this study is the use of a mathematical entity known as a local Lyapunov exponent. This exponent has been shown in past studies (e.g. Lupo et al. 2005 & Hussain et al. 2007) to be a powerful tool in that it is not only helpful in diagnosing atmospheric flow stability characteristics, but also the local predictability of the flow itself. A better understanding of Lyapunov exponent analysis and how it relates to diagnostics already used to study blocking may aid in the development of higher quality forecasts and in turn, better lead time.

3. DATA AND METHODOLOGY

Multiple variables used for this study. The first and most basic dataset was the National Centers for Environmental Predication-National Center for Atmospheric Research (NCEP-NCAR) gridded reanalyses. More detail about this dataset can be found in Kalnay et al. (1996). Archived at NCAR in Boulder, Colorado, these analyses are available from their mass-store facilities. The reanalyses can be located at (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html).

Atmospheric variables in this study included mean sea-level-pressure, 850-hPa mean temperatures, 500-hPa mean geopotential heights, and pressure on the dynamic tropopause.

3.1 The Blocking Index (BI)

For the purposes of basic blocking analysis, the 0000 and 1200 UTC NCEP-NCAR monthly 500-hPa gridded (2.5° lat. x 2.5° long.) mean geopotential height plots were accessed for the event. The Eurasian event covered the months of June through August 2003.

In this study, the blocking criteria used in Lupo and Smith (1995a&b) was employed for analysis. As for the strength of the blocking event, the criterion developed in Weidenmann (2002) as further modified from Lupo and

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Smith (1995a) and Lupo et al. (1997) gives a "blocking index" or BI value, from one to ten. A value closer to ten yields a stronger block, while values closer to one lend to weaker events. The BI equation, given by;

$$BI = 100.0[(MZ/RC) - 1.0] \tag{1}$$

where MZ was the maximum 500-hPa height in the closed anticyclone region or on a line associated with the ridge axis, and RC the subjectively chosen representative contour. Thus, Wiedenmann et al. (2002) shows that the resulting BI values are proportional to the gradients of height in the blocking region. Given this proportionality, the BI can be used as a diagnostic quantity for determining the relative strength, within the Northern and Southern Hemisphere blocking regions, of large-scale flow regimes as Lupo et al. (1997) discussed.

3.2 Pressure on the Tropopause

The second dataset used in this study is the 0000 and 1200 UTC NCEP-NCAR monthly gridded (2.5^o lat. x 2.5^o long.) pressure on the tropopause. Just as with the mean geopotential height fields, the dataset's temporal domain is June through August 2003.

Further investigation into this blocking episode arise from the analysis of distributions of potential vorticity at the dynamic tropopause. In quasi-balanced flow situations, potential vorticity can offer an efficient description of the dynamic characteristics of synoptic to planetary scale flows (Morgan and Nielsen-Gammon 1998). The level of the dynamic tropopause in which analysis is performed is confined to the 2.0 PVU level, as defined in the NCEP-NCAR 40-year reanalysis. Specifically, pressure on the dynamic tropopause is used to diagnose dynamical characteristics of the European blocking event discussed in this study

3.3. Local Lyapunov Exponents

In an effort to study the stability of the blocking flow itself, a method known as local Lyapunov Exponent analysis will be employed to examine the Western European block. The study of flow stability (via Lyapunov 1966) also contains a powerful tool, in that the use of the exponent also examines the predictability within the flow (e.g. Dymnikov et al. 1992).

Lyapunov exponents mathematically arise from the eigenvalue-solutions to the equations of motion, which describe a system's internal dynamics. In the simplest of terms, the exponent describes the time-averaged rate of change of convergence (or divergence) of nearby trajectories in a system. Since these entities are solutions to eigenvalues, there can exist as many exponents as physical system dimensions. In a system in which the sum of the Lyapunov exponents is negative, the system would exhibit a high degree of predictability. In other words, the trajectories within the phase space would converge (as time approaches infinity) towards or approach an attractor. This attractor is located in the center of the so-called "basin of attraction."

The foundations of Lyapunov exponents are rooted in the mathematical theory of infinite dimensional stability. Following this theory, blocking can naturally be seen as a quasi-stationary atmospheric circulation (Lupo et al. 2005). With this basic premise, it becomes apparent that the best way to study this phenomenon is through the characteristics of its stability profile.

In a natural progression of thought, Lupo et al. (2005) showed that stability characteristics of a flow can be seen as analogous to the finite dimensional dynamic systems highlighted in Walters (1982). Moreover, Walters (1982) describes how the examination of "local Lyapunov exponents" was devised for the barotropic vorticity equation.

As shown in Lupo et al. (2005), for an initial vorticity field ω_o and time $T = n\Delta t$, these Lyapunov exponents are in principle given by;

$$\lambda_i(\omega_o, \mathrm{T}) = \frac{1}{2n}\log v_i \tag{2}$$

For v_i the putatative eigenvalues of:

$$\mathrm{M}^*\mathrm{M}, \mathrm{M} = \prod_{k=-n}^{k=n} \mathrm{B}(k\Delta t) \tag{3}$$

where B(t) is the linearization operator of the barotropic equations of $\omega(t)$. Through a process known as a Crank-Nicholson scheme, the above is expressed in a numerical way (Dymnikov et al. 1992).

Given a domain D (specific the blocking event) data over a three-year period is placed through a planetary-scale (15-day) filter. The sum of the positive Lyapunov exponents shows a strong correlation to the linearized barotropic flow eigenvalues as well as the domain-integrated enstrophy;

$$\sum \lambda_+ \approx \int_D |\omega|^2 (x, y)\, dx dy \tag{4}$$

The power of enstrophy (at least as a forecasting tool) is truly shown by the fact that the increasing nature of the sum of positive Lyapunov exponents decreases the average time for the ω-trajectories to diverge (Lupo et al. 2005). Physically, enstrophy is to vorticity as kinetic energy is to velocity.

By using Lyapunov exponents as a rigid treatment of atmospheric blocking flows (in other words a dynamic, infinite dimensional system), one must realize that a theory of Lyapunov exponents in infinite dimensions can be developed (Constantin and Foias 1985). When considering a flow in this context, it is apparent that the domain is one of many possible atmospheric flows as opposed to the classical treatment of Lyapunov exponents of a single, steady flow (Cohen and Schultz 2005).

Thus, the flow will become increasingly unstable if either the maximum absolute value of $\nabla\Psi$ (a representation of the geostrophic wind) or the maximum absolute value of $\nabla\Omega_a$ (a measure of barotropic instability) increase. The opposite is true for an atmosphere that becomes increasingly stable; decreasing values of either $\nabla\Psi$ or $\nabla\Omega_a$ tend to stabilize the flow regime (Lupo et al. 2005).

4. CASE STUDY: WESTERN EUROPE 06-13 AUGUST 2003

4.1 500-hPa Mean Geopotential Height Analysis

Analysis of the 500-hPa mean geopotential height field corresponding to 01-03 and 03-06 August 2003 showed the blocking ridge began to form over the Iberian Peninsula during the early part of August (Figures 1a and 1b). As the block amplified, the strongest blocking signature became evident over the period of 06-09 August 2003. Concurrently, a geopotential height minimum was located over the Atlantic Ocean and registered around 5525 gpm. Over the next two to three days, this feature filled and migrated both north and east towards the European continent. Over the same period, the trough appeared highly symmetric within the Atlantic basin, nearly mimicking the height ridge over Western Europe, except appearing as an upside-down omega as seen in Figure 1c.

The symmetric appearance of both positive and negative height features diminished as the flow became more "sheared" over the next three-day period of 09 - 12 August 2003. In this case, "sheared" is used to convey the appearance of the trough and ridge modifying from neutral to positive. The shearing also acted to amplify the blocking region, allowing the anomalously hot air beneath the blocking ridge to migrate further north and east over Western Europe (Fig 1d). A secondary negative height feature also appeared to deepen along with the upstream block. Accordingly, this period marked the hottest period of the entire blocking episode.

The dissipation of the European block, and in turn, the severe heat wave is represented by the de-amplification of the highly meridional flow into a quasi-zonal flow, beginning around 12 August and reaching full fruition on 15 August 2003 (Figure 1e). Along with de-amplification, the height ridge continued to propagate further east.

4.2. 850-hPa Mean Temperature Analysis

Inspection of the 850-hPa mean temperatures over the same period showed a high degree of correspondence existed between the lower level temperature regime and the 500-hPa mean geopotential height patterns. Over the most severe fifteen days of the European heat wave, the abnormally warm air (22^{o}C–27^{o}C) seemed to be related to two source regions located along a belt between the 20^{o}N to 30^{o}N.

The NCEP-NCAR 850-hPa mean temperature reanalysis from 01-03 August 2003 (Figure 2a) showed a ridge of anomalously warm temperatures gripping much of the Iberian Peninsula. Of particular interest is the 22^{o}C (295 K) mean isotherm, which was nearing the southern boundary of France. Further east, a temperature trough of comparable magnitude and spatial extent existed over the Mediterranean Sea. This particular set-up appeared to show the hot air from the African source region was being funneled northward in a clockwise fashion underneath the temperature ridge located over Western Europe. Support for this is given by the 500-hPa mean height field for the same period. The strong blocking pattern that was present at 500-hPa was in a perfect position to allow for the build up of heat in the lower levels of the atmosphere.

As the positive height anomaly continued to amplify over the next three days, so too did the 850-hPa ridge. In fact, with the 22^{o}C (295 K) mean isotherm covering most of western France, the 27^{o}C (300 K) mean isotherm was nearly touching the southern tip of Spain (Figure 2b).

The most active period of the entire month of August occurred for around six days, starting on 06 August. The amplitude of the 850-hPa mean temperature ridge increased in such a way (over the past three days) that a poleward perturbation was evident in the 7^{o}C (280 K) mean isotherm, located around 73^{o}N. For comparison, the 01 August location of this isotherm was 53^{o}N.

Of particular note is the location of the warmest part of the air mass in relation to Europe. As of 09 August, the 24.5^{o}C (297.5 K) mean isotherm was covering much of eastern Spain, France and the southern tip of the British Isles. Ridging in the temperature field slowly began tilting more positive, as the feature propagated eastward over the European continent. With this eastward propagation, the 24.5^{o}C (297.5 K) mean isotherm continued its northwestward advancement (Figure 2c), eventually covering the whole of Western Europe (as far north and east as 50^{o}N, 10^{o}E).

While the unbearable heat continued to infiltrate Western Europe, a curious flow feature became evident with time. The hot air seemed to be advecting into the amplifying temperature ridge (which owes its existence to the block) via a clockwise circulation from the African source region. Moreover, it is highly possible that the warm air was being heated even further by air mass modification over the Sahara desert in northern Africa. This cyclonic advection into the amplifying ridge diminished and moved eastward as the trough over the Atlantic moved into the region (Figure 2d)

The anomalous heating of the western reaches of Europe finally began to diminish as the 850-hPa temperature ridge bounded by the 22^{o}C (295 K) mean isotherm retreated south

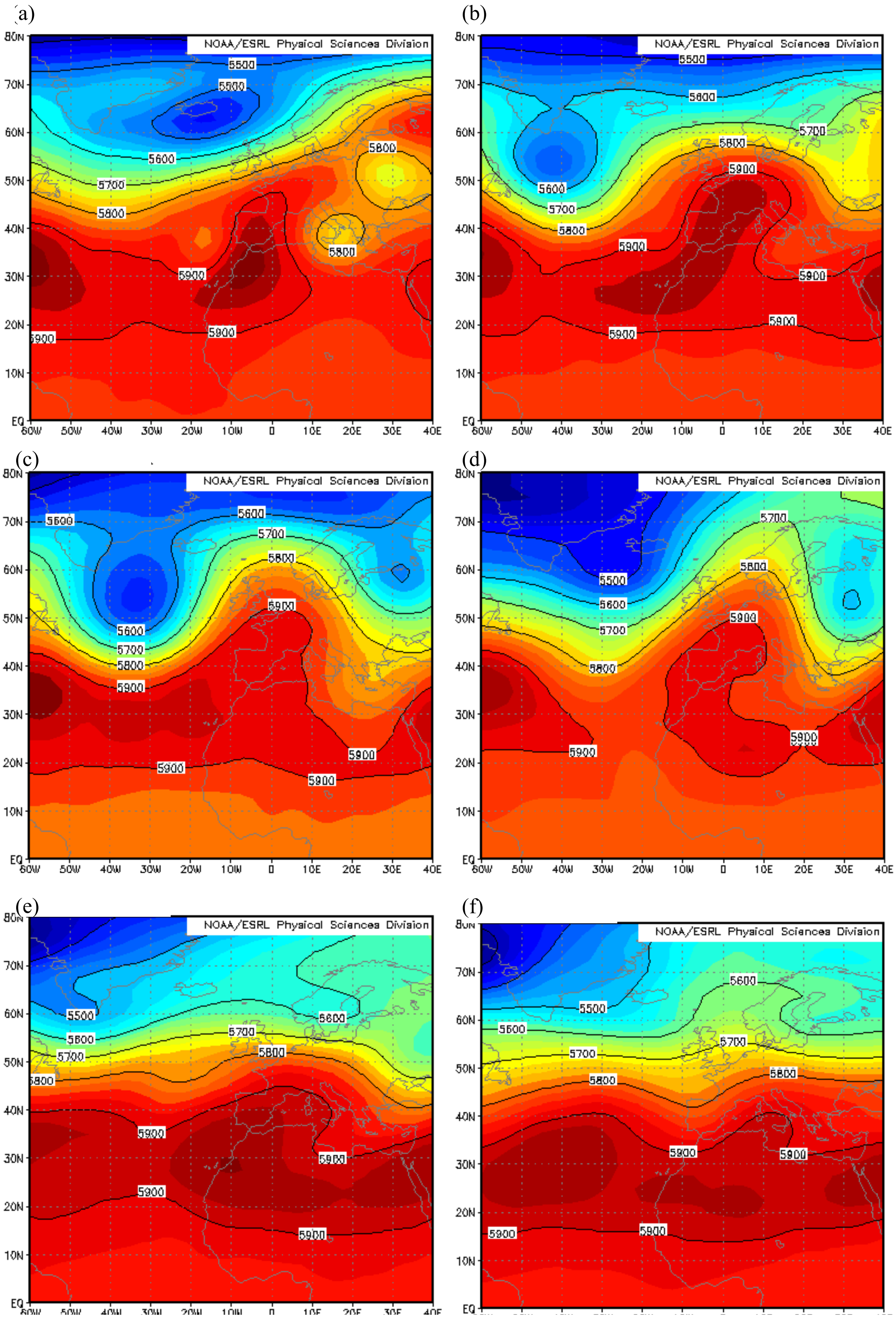

Fig. 1. NCEP-NCAR monthly 500-hPa gridded (2.5^{o} lat. x 2.5^{o} long.) mean geopotential height valid (a) 01-03 August (b) 03-06 August (c) 06-09 August (d) 09-12 August (e) 12-15 August and (f) 15-18 August. Solid black lines represent geopotential height contours (m).

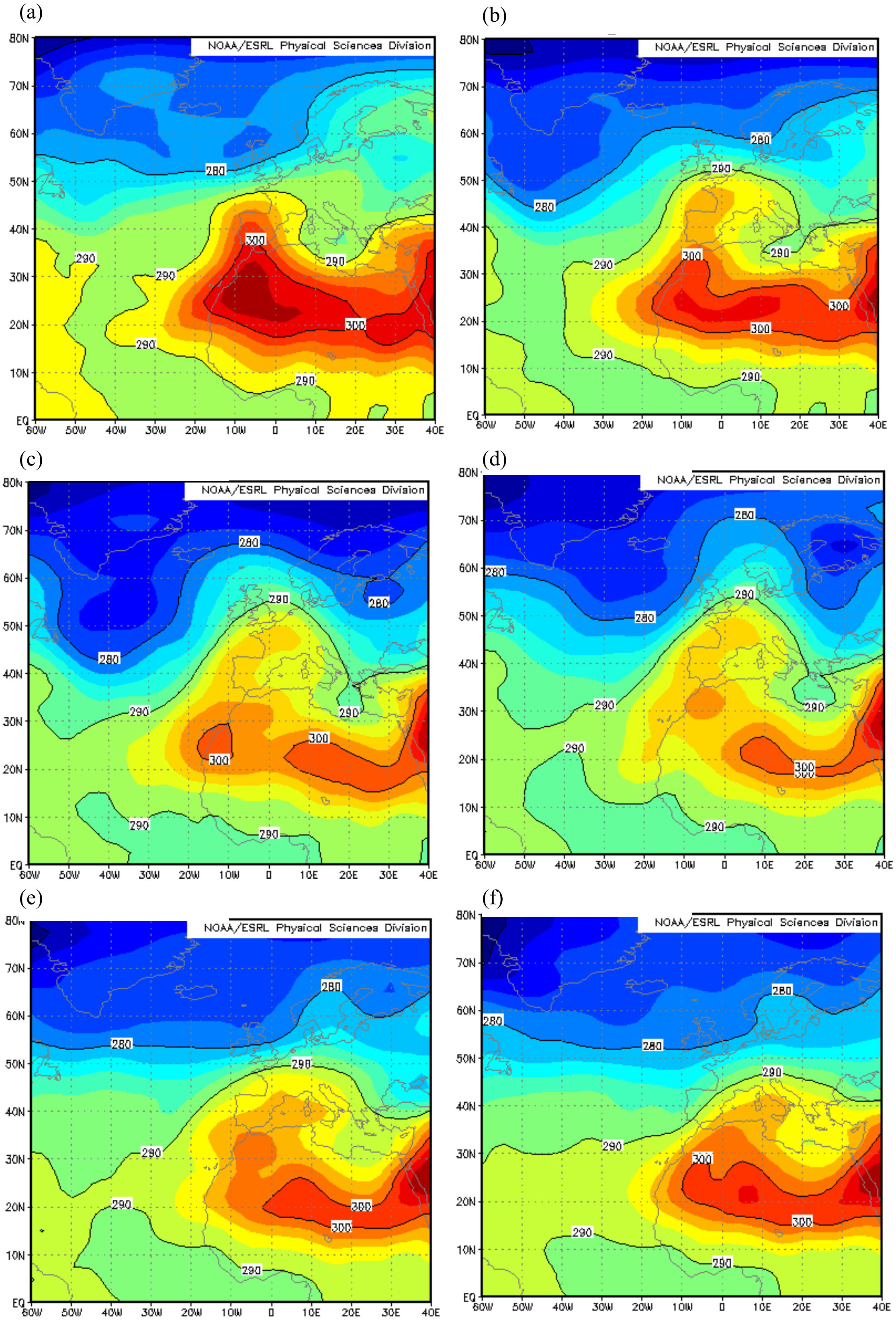

Fig 2. NCEP-NCAR monthly 850-hPa gridded (2.5° lat. x 2.5° long.) mean temperatures valid (a) 01-03 August (b) 03-06 August (c) 06-09 August (d) 09-12 August (e) 12-15 August and (f) 15-18 August. Solid black lines represent isotherms (K).

and east, towards the southern coast of France and western coast of Italy as seen in the previous figure. After 15 August, the 17°C (290 K) mean isotherm moved into the southern parts of Spain and France, as the ridge continued to de-amplify and move over the Mediterranean. Concurrently, the 500-hPa positive height anomaly had almost completely disappeared. The uncharacteristically hot air retreated back to the source regions, as shown by the mean temperature increases in Figure 2e.

5. DYNAMIC ANALYSIS

In this section, pressure on the tropopause was analyzed in two distinct ways. The first type of evaluation involves the entire tropopause-pressure field. This type of examination delves into the planetary-scale contributions to the flow. As discussed in Burkhardt and Lupo (2005), a positive contribution from the planetary scale plays an important role in the development and decay of blocking anticyclones. In fact, the planetary scale provides the background onto which smaller-scale eddies grow and decay, in turn affecting the life-cycle/span of prospective blocking flows.

When evaluating pressure on the tropopause, it is crucial to note that increasing (decreasing) pressure on the tropopause is associated with troughs (ridges), and thus lower (higher) geometric heights (Morgan & Nielsen-Gammon 1998; Lupo et al. 2001). Moreover, pressure on the tropopause was chosen since it is conserved in an adiabatic and geostrophic atmosphere as well as with time. Thus, we can infer that local changes in pressure (at the tropopause) with time are due to quasihorizontal pressure advection.

Since ridging is analogous to low pressure at the tropopause, then a negative Eulerian tendency is beneficial towards block development and infers "low-pressure advection." This may seem counter-intuitive, since low-pressure advection (near the surface) acts to weaken ridges of high pressure. However, the level used for this analysis is the dynamic tropopause, thus low-pressure advection is actually the advection of higher geometric heights.

In an effort to examine the synoptic-scale contributions to the blocking events, the zonal mean is subtracted from the pressure on the tropopause fields. The zonal mean can be looked upon as the neutral component of the synoptic to planetary scale flow regime. When the zonal mean is neglected, a better view of synoptic scale eddies is attained. In fact, the location of cyclones and anticyclones with respect to the blocking ridge proves to be important in the block initiation and decay.

5.1 Pressure on the Tropopause

The 0000 and 1200 UTC NCEP-NCAR daily mean sea-level pressure reanalyses were first evaluated for the three time periods involved in the August 2003 Western European blocking event. These periods correspond to block onset (03 – 06 August), block maturity (06 – 13 August) and block decay (12 – 14 August).

Sea-level pressure (SLP) plots were used to diagnose and evaluate the characteristics of the migratory high and low pressure systems (both upstream and downstream) of the 500-hPa blocking pattern and how they interact with the blocking region itself. These synoptic-scale features also will be important factors when determining the synoptic and planetary contributions throughout the lifespan of the this event.

Troughing in the SLP field is evident in Figure 3, as two areas of low pressure (1009-hPa) developed upstream of the initiating block. The trough was situated poleward of 50°N and centered at 40°W. Over the North Sea, a strong ridge of high pressure (1026-hPa) was found, with the 1020-hPa isobar covering most of west-central Europe.

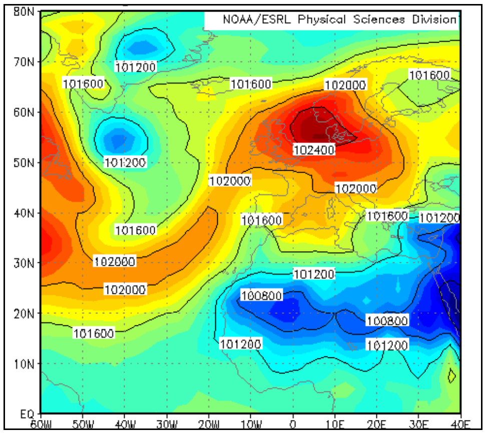

Fig. 3. NCEP-NCAR monthly gridded (2.5° lat. x 2.5° long.) mean sea-level pressure valid 03 – 06 August 2003. Solid black lines represent pressure (Pascals).

The period from 06–13 August (Figure 4) saw the trough deepen over the western Atlantic basin while the high-pressure ridge over Western Europe weakened. At block decay, the 1000-hPa trough continued to deepen as it retrogressed peculiarly further west, over Greenland. The older area of high pressure intensified over the western Atlantic basin as the block at 500-hPa de-amplified (Figure 5). In lieu of this behavior, it is then likely that the synoptic-scale has not commenced reinforcement of the block, similar to results found in Lupo & Bosart (1999).

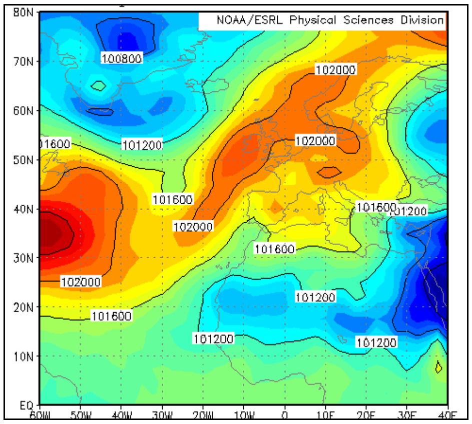

Fig. 4. Same as Fig. 3 except valid 06–13 August 2003.

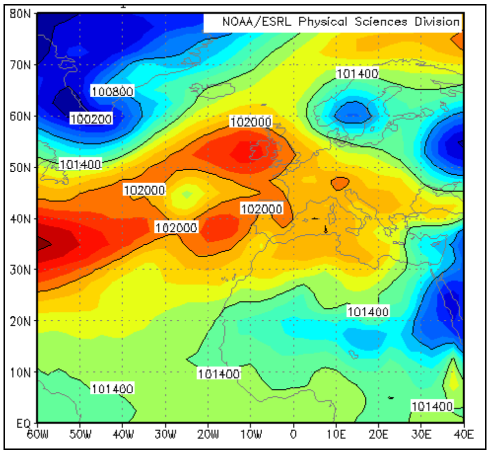

Fig. 5. Same as Fig. 3 except valid 12–14 August 2003.

Corresponding to these surface pressure features, a large region of higher tropopause extending to 60^{o}N was located in the mean tropopause-pressure plot. The amplitude of the ridge was nearly 20^{o} and produced an omega-like structure in the field (Figure 6a). Also of note was an anomalously lower tropopause over the surface low-pressure trough found in the mean SLP plots. As the block continued to develop, the tropopause began to lift. This is particularly evident in Figure 6c. A region of tropopause falls were found on either side of the tropopause ridge, extending poleward from 40^{o}N. Pressure gradients within the tropopause troughing were much tighter than those found in the apex of the tropopause ridge. This ridge was also found to have migrated further west over Central Europe.

As the positive height anomaly at 500-hPa de-amplified (12 – 14 August), so too did the positive pressure anomaly at the tropopause. The dissipation of the pressure ridge allowed the tropopause to lower to a more climatologically expected level.

Considering the anomalous ridging of the tropopause over the block period, and the corresponding pressure ridging throughout the layer, it is apparent the planetary scale contribution (to the blocking event) is positive. With a contribution as such, the block was strengthened continually for a majority of the mature phase and only started to decay as the ridging halted.

Removing the zonal mean from the pressure on the tropopause plots was the next step in analyzing the interactions between the flow and the blocking ridge. In removing the zonal mean, the synoptic scale contributions become more evident and easier to analyze.

At the onset of this blocking event, the strongest mean positive eddy pressure anomaly (80-hPa) was found 40^{o} upstream from where the 500-hPa blocking ridge is expected (Figure 6b). This distance represents about half a wavelength from the center of the blocking ridge. Studies suggest (e.g. Konrad and Colucci 1988; Lupo and Bosart 1999) along with the results found in this section, that cyclonic development (found in the mean SLP charts) within a distance of one-half wavelength from the center of the downstream block contributes to the intensification of the block.

In fact, during the 06 - 13 August 2003 period, the upstream anomaly weakens to 40-hPa as its negative downstream counterpart (co-located with the block) intensifies to -40-hPa (Figure 6d). This result suggests a downstream advection of energy from the upstream cyclone into the block, effectively strengthening the block while producing anomalous tropopause ridging. The scale of the positive eddy anomaly and it's apparent contribution to the blocking region suggest a positive synoptic contribution as well, perhaps even more so than the planetary scale.

The final figure couplet (Figure 6e and 6f) details decay onset for the different scale interactions. It is very interesting to note that during the two-day period beginning on 12 August, the eddy pressure anomalies (both positive and negative) shrank while becoming flatter (with respect to latitude), as the synoptic scale contribution decreased.

Table 1 shows the contributions at each scale of the Eulerian pressure advection at the tropopause. Positive (negative) values represent a negative (positive) contribution. It is important to remember that these values are averages over the entire period.

Table 1. Eulerian pressure advections and contributions to each scale

Onset (hPa/day)	Maintenance (hPa/day)	Decay (hPa/day)	Scale Contribution
-1.6	9.5	-12.5	Total
3.4	-2.1	-12.5	Synoptic
-5	11.6	0	Planetary

5.2 Local Lyapunov Exponents

Local Lyapunov exponents are powerful because they can be utilized as a diagnostic tool when studying the degree of predictability in local flows. Inherently, this examination of predictability lends to the study of the flow stability itself. Consequently, Lyapunov exponents prove to be highly potent in their description of dynamic flows, since the equations governing the flow need not be explicitly solved.

When implementing these exponents in this study, it became apparent that the stability (rather stability changes) of the large-scale planetary background flow are key in all phases of the blocking episode. As will be shown, abrupt changes in the planetary flow greatly correlate with abrupt changes in exponent variability over a given temporal period.

The graphical representation of the exponent, the sum of positive Lyapunov exponents, is placed along the ordinate with respect to time. The temporal spacing is placed along the abscissa for a stationary box of a given latitude and longitude (representing the spatial domain of the blocking region) as seen in the Lyapunov figures.

When diagnosing atmospheric flow regimes using Lyapunov exponents, regions having relatively smaller positive values (on the vertical axis) are highly correlated to blocking episodes in both hemispheres. As stated earlier, abrupt changes in the "positiveness" of the exponent can be used to pinpoint the time periods and trends relating to certain

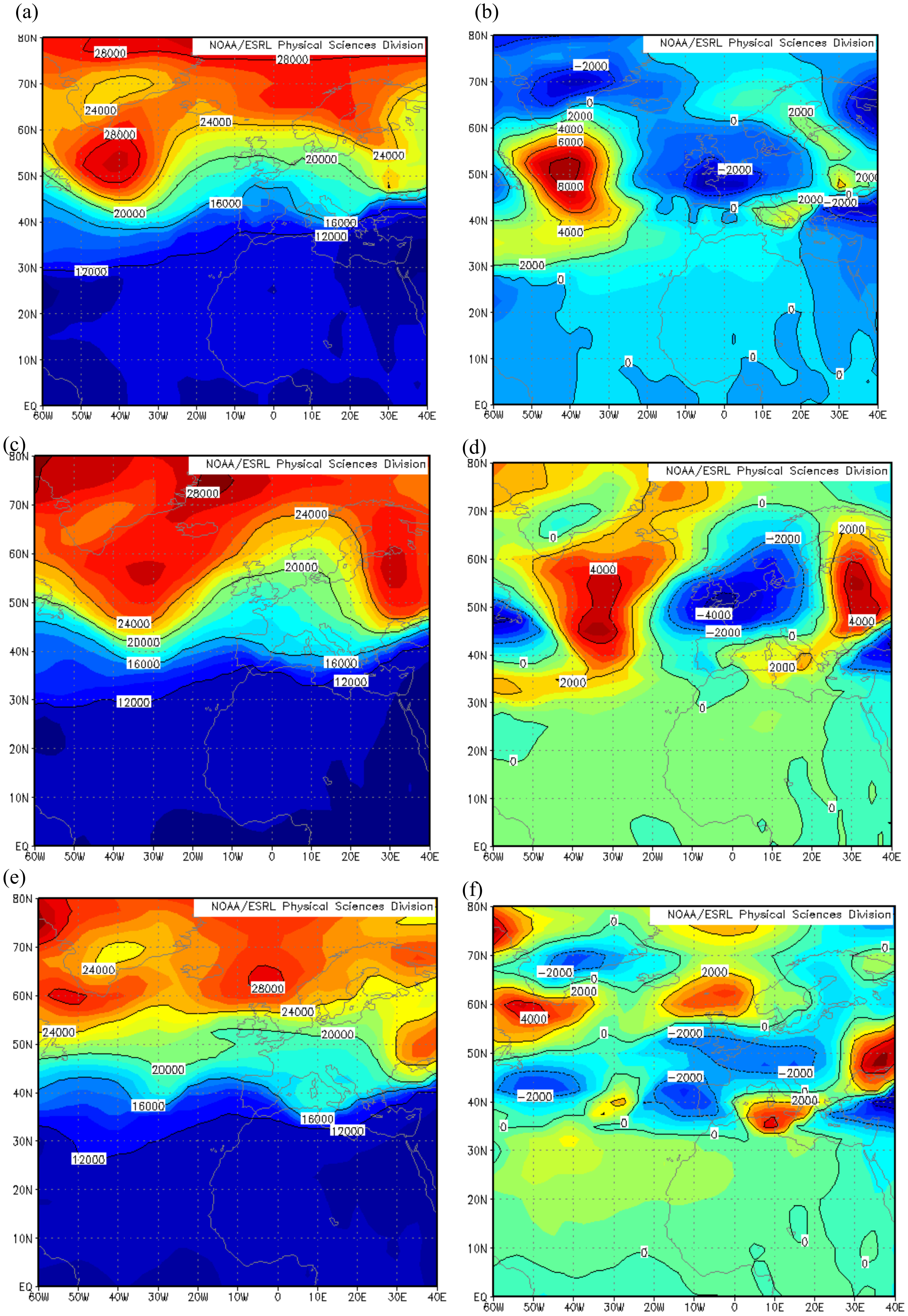

Fig. 6. NCEP-NCAR gridded monthly mean (2.5° lat. x 2.5° long.) (a,c,e) pressure on the tropopause & (b,d,f) eddy pressure on t tropopause. Figure set one valid 03-06 August 2003, figure set two valid 06-13 August, and figure set three valid 12 -14 August 2 Solid black lines represent pressure (Pascals).

stages of the blocking flow (i.e. initiation, maintenance, and decay).

Also of note, the sum of the Lyapunov exponents is analogous to the area-averaged enstrophy of the dynamic system. Enstrophy, as a physical quantity, is merely one-half the square of relative vorticity and conserved in two-dimensional invicid flows (Leith 1968). Enstrophy becomes important in understanding the dissipative effects of large scale eddies on various flow regimes, including blocking.

For all calculations herein, the 500-hPa 0000Z data was used, as well as the latitude box covering 20^{o}-80^{o}N. The longitude box is valid for the blocking region. Limitation of the longitude box produced higher quality output and thus more specific results.

When considering the Western European heat wave of 2003, the period of 01–15 August 2003 is highly important, since this span of time was when the blocking anticyclone was at its strongest. Analysis of the Lyapunov exponents (confined to a longitude box covering 60^{o}W to 40^{o}E and a latitude box covering 20^{o} to 80^{o}N) showed a steep decrease in the positive nature of the exponent in the period directly preceding block initiation (Figure 7). This behavior is expected, in that the flow becomes more predictable when the sum values of the exponent are closer to zero. A greater degree of variability is evident from around 05 – 08 August as the block matured, with Lyapunov values spiking to around 1.4x10^{-10}, the second largest peak in the 31 day period. After this brief period of flow instability, the blocking regime stabilizes until the blocking pattern begins to decay on or around 12 August.

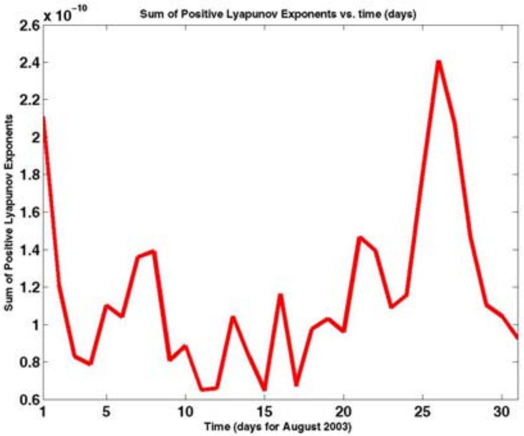

Fig. 7. The area-averaged enstrophy. Lyapunov exponents are found on the ordinate with respect to time (days), along abcissa represents the stationary box (60^{o}W to 40^{o}E and 20^{o}N to 80^{o}N) in the mid-latitudes of the Northern Hemisphere. Valid from 01 – 31 August 2003.

This analysis is consistent with the premise that a minimum state of enstrophy (a more stable flow) should represent the blocking flow as seen in the less-positive nature of the Lyapunov exponents. This pattern in the exponents suggests that during block maintenance, the flow regime is highly stable and only begins to dissipate as the planetary scale vacillates to another phase (i.e. dissipation).

6. SUMMARY AND DISCUSSION

When evaluating the Western European event of summer 2003, plots of pressure on the tropopause show a positive contribution (i.e. a situation in which block development was more likely to occur) to the onset and maintenance of the blocking anticyclone. Extreme gradients, especially during the mature phase of the block, were also found in the tropopause pressure fields. These gradients developed on the boundaries between the planetary scale ridge/trough couplet covering the entire domain of the blocking region.

For the purposes of synoptic examination, the zonal mean was subtracted from the mean tropopause pressure plots. This analysis technique allows for the examination of synoptic scale eddies and their interaction with the blocking ridge itself. During block maintenance, a positive pressure feature was found less than one-half of a wavelength from the central axis of the block (and co-located with a surface cyclone). This suggests Eulerian low-pressure advection and in turn, the advection of higher geometric heights. Higher geometric height advection into the blocking ridge effectively amplified and strengthened the European block.

The resulting interpretation shows that indeed the planetary scale (troughing and ridging) played an important role in blocking onset and maintenance, but a stronger contribution form the synoptic scale eddies (cyclones and anticyclones) allowed the Western European event to strengthen. This intensification only reinforced the heat wave occurring over Europe. It is interesting to note, however, that planetary contributions appeared to produce a more positive role during block decay, as the planetary flow shifted into a new geostrophic phase.

The breakdown of this event showed the synoptic scale eddies fed on energy from the larger scale background. Due to this, positive energy contributions on the planetary scale filtered down into the synoptic scale. In turn, these eddies advected higher geometric heights into the blocking ridge, greatly amplifying the block until a point in which the planetary scale ceased or slowed its downward energy transport. When this occurred, the planetary scale began to change the character of its flow stability profile, thereby vacillating into a new, more zonal phase. This process effectively pacified the meridional flow regime, which is of the utmost importance for block maintenance.

Changes in the flow stability character of the planetary scale are not inherently obvious in the synoptic or dynamic analyses. Moreover, the predictability of such changes (especially when considering blocking anticyclones) is one of the major shortcomings in the study of atmospheric blocking. Extreme cannot be prevented, as they are naturally occurring atmospheric phenomena. Nevertheless, if forecasts for blocking onset were possible, the economic, social and societal effects may be mitigated by advance preparation alone. The mathematical entity known as the local Lyapunov exponent appears to be one of the most promising weapons in the arsenal of blocking diagnostics and thusly, a way of producing higher quality forecast as well as greater forecast lead-time. These exponents, as discussed previously, are very powerful in that they can be utilized when studying the degree of stability of a given atmospheric flow. Understanding stability lends to the understanding of flow predictability. In this study, local Lyapunov exponents were used to evaluate atmospheric flow characteristics directly related to blocking anticyclones. The results of chapter four reveal a surprising connection between the behavior of the atmospheric flow (directly preceding block onset/decay) and the change in character of the sum of positive Lyapunov exponents.

The onset of the European block began on 03 August 2003. Following two days of initial development, analysis showed the block reached full intensity until 12 August when the block began to decay. When the sum of positive Lyapunov exponents is plotted versus time, several interesting features arise. The first, and perhaps most significant (as Figure 7 shows) was a steep drop in the "positiveness" of the exponent (around $1.3x10^{-10}$ in just over one day). Since a less positive exponent represents a stabilizing atmosphere, it becomes apparent that a major shift in the planetary flow was occurring just prior to block initiation. After the onset of the blocking event, a slight rebound was prevalent and remained until the block began to dissipate. One would expect relatively smaller positive values since a blocking regime represents a minimum state of enstrophy, and thus a more stable flow. Only immediately before block decay did the exponents begin to decrease towards the monthly minimum enstrophy. This action alone mimics the temporal period prior to blocking onset.

The consequences of the exponent analysis are fascinating in that a highly noticeable pattern emerges in the sum of positive Lyapunov exponents. In this cases, a steep decrease in enstrophy preceded the initiation of a blocking anticyclone. Correspondingly, a steady decrease of enstrophy also preceded blocking decay. Taken individually, when the exponents became less-positive, a transition in the stability profile of the planetary scale flow ensued. Only after block onset did the exponents remain stable. This represented a quasi-complete transition form a zonal current to a highly meridional (and thus blocked) current. The decay of the block merely signified the reversion of the high amplitude flow back to a more zonal orientation.

In terms of stability, the basic premise found in the exponent analysis is one of the planetary scale flow becoming highly unstable prior to block initiation and dissipation. Moreover, this oscillation between flow states coupled with the fact that blocking flows are inherently stable suggests the buildup of gradients produces the necessary background instability for planetary scale flow transitions. This analysis demonstrates the power of local Lyapunov exponents (and the related physical quantity of enstrophy) in the study of blocking regimes and large-scale flow transitions.

Local Lyapunov exponents, with respect to pressure on the tropopause, appear to add strength (and in so doing, extra power) to this diagnostic quantity. While Lyapunov exponents offer an astonishing look into the changes in the flow regimes on the planetary scale, mean tropopause pressure plots aid in the identification of synoptic scale eddies. These smaller scale structures effectively feed on energy from higher scales. Section 5 produced a dynamic examination of how the processes on the small (synoptic) and large (planetary) scales interact in the formation, maintenance and decay of blocking events. Since each scale provides a positive contribution, in terms of blocking onset and decay, a correlation should exist between changes in the advection of pressure at the tropopause and changes in the Lyapunov exponents. Changes in these pressure advections correspond to changes in the advection of geometric heights. These height elements coincide with features found throughout the atmosphere (e.g. surface cyclone, 850-hPa thermal ridges, 500-hPa height anomalies, etc.). Any abrupt changes within the planetary scale flow produce ensuing modifications in these structures and hence modification to weather patterns in general. As a result, changes in intensity or the propagation of these tropopause pressure eddy anomalies should lend credence to concurrent changes in the large-scale flow itself. Dynamically, every atmospheric scale is connected. Accordingly, the changes suggested above should be mirrored in the behavior of the local Lyapunov exponents. The results from the dynamic analyses appear to verify this statement.

7. CONCLUSIONS

Using dynamic analysis of pressure on the tropopause plots as well as synoptic analyses, it was found the planetary scale provided a background environment conducive to block development and maintenance. During the mature phase of the block, there existed extreme large-scale gradients in the mean tropopause pressure fields. These gradients developed on the boundaries between the planetary scale ridge/tough couplets that were present in each of the studied events. The atmospheric instability produced via these gradients allowed for the transitioning between atmospheric flow regimes, include that of the blocking phase itself. It is important to note that synoptic scale processes also augment the planetary scale contributions.

Since the favorable planetary scale background existed, synoptic scale eddies were allowed to form upstream and downstream of the blocking anticyclone (near the large gradients). Upstream interaction of surface cyclones (within one-half wavelength from the blocking ridge axis) acted to amplify the blocking anticyclone.

In this case study, planetary scale energy augmented synoptic scale processes, which induced further amplification of the blocking ridge. Concurrent with the strengthening of the blocking event, gradients on the planetary scale also increased in intensity. This give and take of energy between scales eventually led to the de-amplification of the meridional flow and the dissipation of the blocking anticyclone.

The findings are remarkable in that these exponents show great promise in understanding the large-scale flow characteristics seen in atmospheric blocking. When each case was examined using plots of the sum of positive Lyapunov exponents versus time, a steep decrease in enstrophy always preceded the initiation of a blocking anticyclone. Correspondingly, a decrease in enstrophy preceded blocking decay. Taken as a whole, when the exponents became less-positive, a transition in the stability profile of the planetary scale flow ensued. After block initiation (dissipation) the exponents remained stable, representing a quasi-complete transition from (to) a zonal flow to (from) a highly meridional, and thus blocked, flow.

When discussing the character of stability, the most essential feature found in the analysis of area-averaged enstrophy (given by Lyapunov exponents) is one of the large-scale flows becoming highly unstable prior to block onset/decay. One of the physical mechanisms responsible for this is the build-up of instability via gradients in the temperature and mass fields. Once enough instability has been accumulated, the flow is forced to find a new geostrophic state.

The vacillation between flow states and the fact that blocking flows are inherently stable support the statement above. Furthermore, the power of local Lyapunov exponents is highly evident from the analyses provided in this study. Not only can these entities determine local fluid stability (or changes in stability), they also aid in the analysis of the predictability of large-scale flows, specifically atmospheric blocking.

Local Lyapunov exponents do an exceedingly great job determining the onset and decay of blocking flows. This study has shown the interconnectivity between the planetary and synoptic scales when examining blocking events. When probing the character of the planetary scale flow regime, it has been shown that any abrupt changes within this scale produce resulting modifications on synoptic scale structures and in turn, alterations to weather patterns in general. As a result, changes in intensity or the propagation of eddies in the tropopause pressure fields should signal large scale flow restructuring. Since planetary flow vacillations produce changes on the smaller scale, these subsequent synoptic adjustments should be emulated in plots of the sum of positive Lyapunov exponents.

Finally, the results found in this study have shown the power of local Lyapunov exponents as a means of determining the onset and decay of an extreme case of atmospheric blocking. While ensuing extreme weather phenomena cannot be prevented, the possible implication of the local Lyapunov exponent analysis points at the possibility of the creation of higher quality block onset forecasts and extended lead time for forecasts in general. Additionally, it has been shown the degree that planetary scale plays a role in the development and maintenance of blocking anticyclones. While this scale may not directly produce blocking events, it certainly creates the background character conducive for synoptic scale processes via eddies formation and interaction. Due to these interactions, manifestations of the block itself are found throughout the atmosphere, whether as a surface anticyclone, an 850-hPa thermal ridge, a 500-hPa positive height anomaly or as a positive pressure eddy on the tropopause.

Intrinsically though, the dynamic and synoptic description of atmospheric blocking (as detailed in the analyses contained in this study) is matched in power by the Lyapunov exponent examination. By understanding the concept of enstrophy and the basic premise set forth in Lupo et al. (2005) "…that atmospheric blocking should be thought of as a quasi-stationary circulation whose state is best analyzed by its stability characteristics," a profound realization is created in that the promise of an eventual understanding of the stability character of atmospheric blocking will lead to a more complete knowledge with respect to the predictability of large scale atmospheric flows.

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