Synoptic systems: flow-dependent and ensemble predictability

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1. Introduction

When I look at the forecasting maps in the operational room, I often wonder to which extent I should believe to a certain meteorological feature present on the map. Will it really occur? Is it a realistic feature? Is it really possible to predict such a detail so far in to the future?

These questions have been around from the beginning of operational forecasting and are very important for a successful forecasting procedure since "no forecast is complete without a forecast of a forecast skill" (Tennekes et al. 1986). These questions reflect also the degree of consciousness of the forecaster, the extent to which he/she understands the limitations of a given forecasting system and especially they reflect his/her knowledge on the chaotic nature of the atmospheric motions. Errors are obviously present in the definitions of the initial conditions and in the model formulation but the net impact on the forecast accuracy will critically depend upon their projections on flow dependent instabilities. Although since its beginning, operational forecast accuracy has drastically increased via initial error reduction and better model formulation, nonlinear growth of errors can be large and unavoidable under some conditions. The recognition of condition leading to rapid error growth, rather then days with exceptional low growth, it is then a key issues for operational forecasting, allowing forecasters to tune their confidence accordingly. In general, if we recognise a situation more predictable we could provide more details, or we can push the forecast at longer time ranges. In less predictable situations we are bounded to provide only broad and less detailed information and restrict our deterministic prediction to shorter timescales. Ensemble forecast system, by measuring the rate of divergence of slightly different simulations, have been designed to objectively estimate the predictability of the day. Understanding flow dependant predictability it is also important for model diagnostic. Studying the flow dependency of errors might help to identify model deficiencies and guide specific research efforts, eventually providing indication where to focus further development like in modelling or in data assimilation for example. In this contribution we will discuss and provide some evidence of the different level of predictability associated at some characteristic synoptic flow. In this contribution we will make use of the following basic concepts as summarised by Lorenz (2006):

> *"Predictability or Intrinsic Predictability: the extent to which prediction is possible using an optimal procedure. This represent an upper limit and it is essentially determined by the stability properties of the atmospheric flow.*
>
> *Practical predictability or predictive skill or forecast accuracy: the extent to which we are currently able to predict with current procedures."*

2. Is the forecast accuracy dependent on the flow? A brief review

Grønaas (1982), did show that the skill of medium range forecast can be very different according to different large scale synoptic situations. In particular he provided an example over two weeks in December 1981. In the first week, high score (higher than average) between day 5-7 were observed over the European area. The flow over that period was characterised by a stationary wave train of Rossby waves. The next week, characterised by a transition to a zonal flow, was scoring quite badly. In a longer statistic it showed that the difference in skill at medium-range over periods of 3 months could be quantified in about 2 days (from ondulated/blocked flow to zonal flow). He observed that the skill was higher when a wave train was already present in the analysis or predicted in the very short-range but the forecast was not that accurate in developing the wave train in the medium-range. Another example of was provided by Palmer et al. (1989). They found a strong correlation between PNA patterns and medium range forecast skill. With PNA negative (ridge over NE-PAC) forecast skill tend to be poor over NH. Tibaldi and Molteni (1990) investigated the predictability of blocking, finding that frequency was severely underestimated in medium-range forecasts; the model was reasonably skilful when the blocking was already present in the initial conditions, but blocking onset was very poorly represented if it occurred more than a few days into the forecast. The examples above show how the predictive skill of a forecasting system clearly depends on the flow pattern with a complex interplay between model errors and property of the flow.

From those early days the situation has definitely improved, the predictive skill of the system has increased.

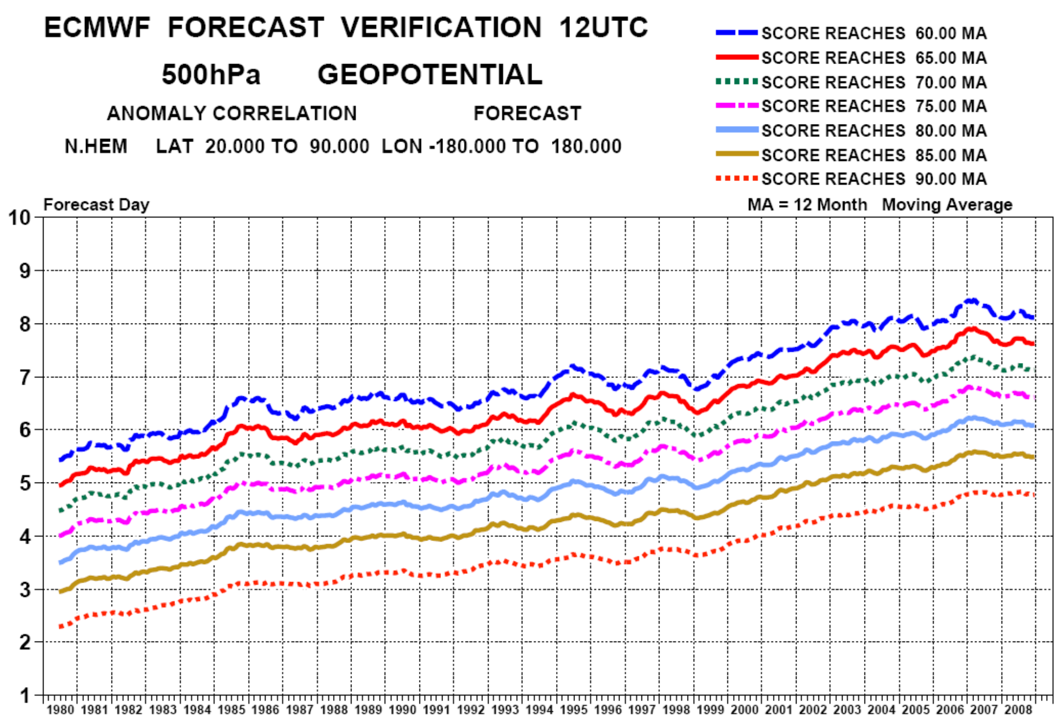

Figure 1: Trend of ECMWF forecast accuracy measured by anomaly correlation of geopotential height at 500 hPa reaching different thresholds. Source ECMWF web site

As shown in fig.1, the actual ECMWF forecast accuracy (measured in terms of anomaly correlation of Z at 500 hPa) at D+7 it is similar to the accuracy of the forecasting system in the 90's at a range of D+6 and D+5 and similar to the one achieved at D+4 in the 80's, at the beginning of operational forecasting . Roughly, over the last 30 years the forecast accuracy in the medium-range has increased by 1 day per decade. Nowadays, on average, a 8 days forecast can be considered still useful or above the threshold of 60% anomaly correlation.

This remarkable achievement has been obtained through a continuous improvement of the realism of the model (Simmons et al. 1995, Bechtold et al. 2008) and a giant improvement in the definition of initial condition with the introduction of 4Dvar, relaying more and more on increasing observations from remote sensing. However this improvement in forecast accuracy has to be considered true for average conditions since it is computed over many days and seasons with very different flow patterns and atmospheric states. Atmospheric predictability and model errors are highly flow-dependent therefore an increase in skill for average conditions may not imply that the same improvements have occurred in specific conditions, like in high-impact weather situation for example, where we would like to have very good guidance from the model.

It is therefore interesting to understand how refinements in the forecasting systems have projected on to the ability to predict different synoptic patterns. Mureau (1990) showed that the systematic errors (defined as the time-mean error and representing the steady drift of the model) has been reduced drastically with model improvement occurred through the 80's due for example to the introduction of the envelope orography first (Tibaldi, 1986) and then with the parametrization of sub grid effect of surface and gravity wave drag (Miller et al., 1989). The reduction it has been obtained in particular through improved prediction of long-waves. In the early 90's the impact of seasonal systematic error was reduced only to 5% of total forecast error at D+10. However shortening the averaging period to 10-20 days and reducing the spatial averaging domain to a regional scale (like Europe) revealed that such improvement was not as great as on global scale and was very much dependant on the meteorological situation during the averaging time. In a later work Ferranti et al. (2002) investigated with a singular value decomposition analysis the link between systematic errors and flow type. They found that in the medium range the errors over the Atlantic associated with NAO-like oscillations become dominant over the north hemisphere. In particular they found that error growth associated

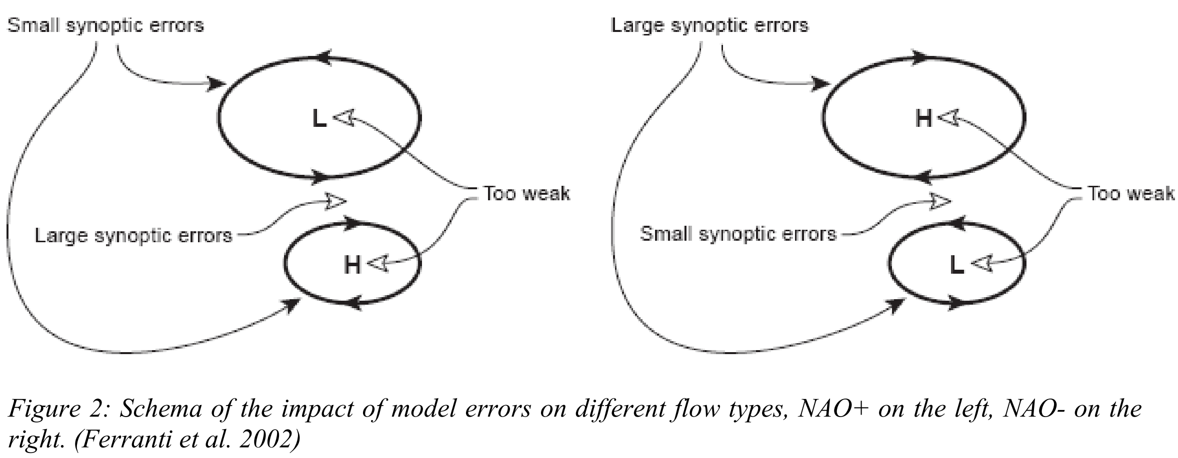

Figure 2: Schema of the impact of model errors on different flow types, NAO+ on the left, NAO- on the right. (Ferranti et al. 2002)

with a positive NAO phase is strong in correspondence of the jet maxima, affecting the propagation of the westerly flow and the highly baroclinic structures embedded in it, like growing cyclones in the in the left exit of the jet. Error growth in these situations is generally very rapid. In the negative phase of NAO (characterized by large waves or a reversed gradient) the largest errors are not in the transient flow but more associated with the orientation/intensity of the large scale wave. Summarising in a zonal like flow error growth is fast (exponential) and affects more the synoptic scale, in more ondulated flow type error growth is slower and errors are affecting more the large scale as summarised in the schema in fig.2.

We now examine how improvements in the forecasting system have projected on the forecast accuracy of a particular flow type, thought to be a large-scale precursors of heavy precipitation events over the Alps. This meteorological configuration has been described by Martius et al. (2006) and Grazzini (2007) (fig.3), hereafter will be called for brevity SSF (Strong Southerly Flow impinging on the Alps).

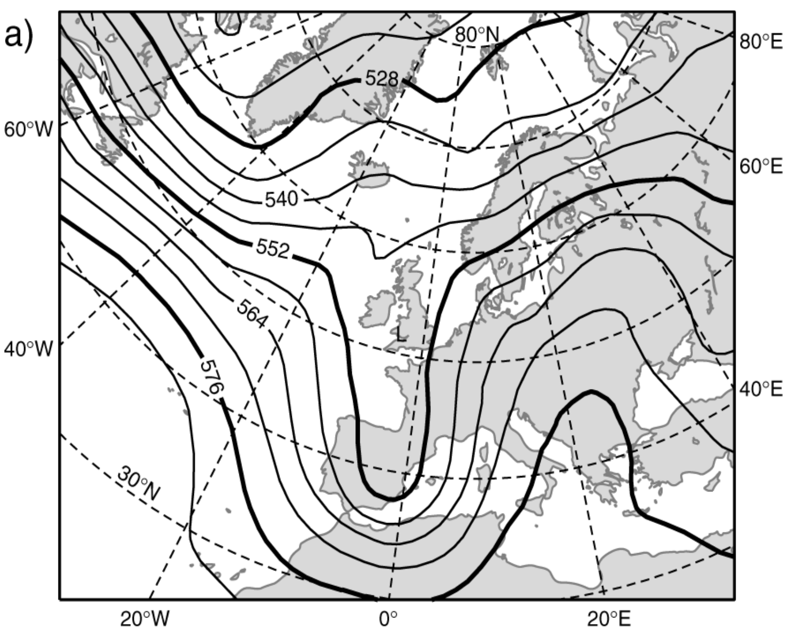

Figure 3: Reference patter, in terms of 500 hPa Z, associated with heavy precipitation on the south side of the Alps.(Grazzini 2007)

An analysis of forecast accuracy in predicting this specific configuration is presented in the work of Grazzini (2007). He found that usually forecast that verifies on days with SSF configuration are more accurate than average days, adding further evidences in favour of the idea suggested by Grønaas that this type highly ondulated flow is more predictable than average zonal flow. In figure 4 are presented the scores based on root mean square forecast errors computed over the European domain, stratified by decades and by days with/without SSF. It can be seen that the predictive skill of ECWMF system is higher for days with SSF. Similar results were obtained using as metrics the anomaly correlation coefficient. From the comparison of the curves from the two decades we could also see that system changes occurred through the years had a greater positive impact on SSF condition, dominated by very large scale waves. Results are summarised in table 1.

Table 1: Summary of the predictive gain due to the error reduction in the operational forecasting system from the 80's to the 90's.

D+6	All	SSF
ACC	+8%	+12%
RMS	14 m	26m
Predictive gain	18 hours	30 hours

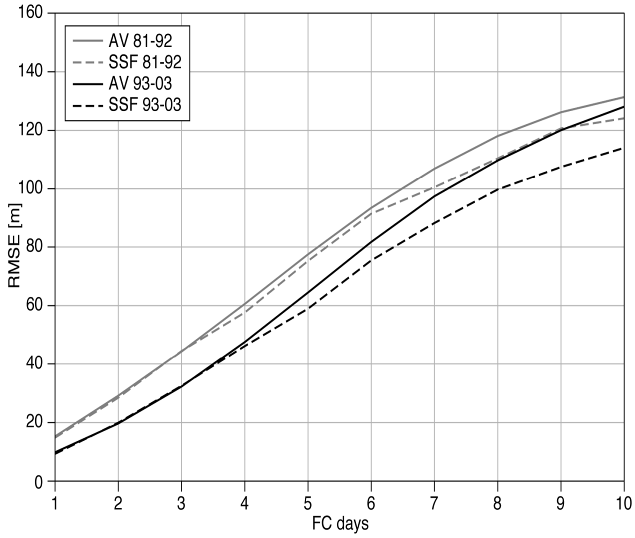

Figure 4: The solid lines represent the average forecast RMSE for all spring and autumn days, regardless of the flow pattern. The dashed lines are the same but with forecasts verifying on spring and autumn SSF cases only. Grey lines are referring to the period 1981–1992 (68 SSF cases), while black lines are referring to 1993–2003 period (70 SSF cases). All curves refer to average scores computed over the European area (75–35N, 12.5W–42.5 E). (Grazzini 2007)

In the same work the author confronted the evolution of the skill of operational medium-range forecast, for SSF and normal conditions, against ERA40 forecasts. The skill of ERA40 forecast, being the integration model kept fix in time, is assumed to be function only of the quality, density and type of the observations available in a certain period, while the skill of the operational model is instead function of both model/analysis characteristics (changing in time) and observations used to formulate the initial conditions. A comparison between the two may highlight forecast skill sensitivity to one component respect to the other. This comparison essentially show a greater impact of model changes respect to sensitivity to initial conditions, with ERA40 reforecast (benefiting of a more a recent version of the model 23r4, in operation between 2001 and 2002) much better than operational model for average conditions, with larger improvement for SSF event. Results are indeed confirming that in the early days systematic errors were very detrimental for the prediction of long waves. The introduction of spectral model, a better formulation of the model orography, the increase in resolution, the introduction of a parameterisation of sub-grid gravity wave drag, all contributed to increase the extraction of momentum from the flow, reducing the speed bias of the westerlies with the net result to improve the modelling of the ultra-long waves (Woods 2006, pp. 105–107). So far we have mainly discussed the evolution of the predictive skill operated by the reduction of flow dependent systematic errors associated with long waves. Now we are going to discuss whether the observed increase in skill during SSF could also be attributed to higher potential predictability of this pattern.

3. Potential Predictability of SSF conditions

The appropriate tool to investigate predictability dependencies on the flow is clearly an ensemble prediction system. We start analysing a case study taken as representative of the performance of the ECMWF EPS in this conditions. As can be seen in figure 5 the deterministic forecast exhibit a very good consistency in Z500 already in the medium-range. Forecast consistency can be taken as a measure of potential predictability as discussed extensively in early studies from Lorenz (1982) and more recently revisited by Bengtsson and Hodges (2006). As far the ensemble was concerned also the ensemble mean did show a synoptically consistent signal already in the medium-range, the spread of the ensemble was low. There were therefore indications of an high level of predicatibility for the large-scale. To further substantiate the hypothesis of enhanced predictability, we computed a composite of the ensemble spread of 69 Z500 D+5 forecast verifying on SSF days and we computed the standardized anomalies respect to normal conditions. As can be seen in figure 6 from the contours of standardized anomalies, despite being not to large in absolute terms (up to +1 standard deviation in the west side of the through, up to -0.75 in the ridge on the east side of the high pressure), there are indications for an increase in spread associated with the positioning of the strong gradient of the through and a larger area with lower spread than normal associated with a consistent prediction of the blocking high on the east. This simple analysis support the perception gained in operational forecasting that these events, well captured in the medium-range and consistently handled by the forecasting system, are indeed more predictable.

Grazzini (2007) and Martius et al. (2008) have found that SSF conditions are mainly triggered by wave breaking at the end of a Rossby wave packet travelling from upstream regions. As we try to clarify later, higher level of predictability might be due to the presence of the wave packet and the pre-existence a blocking high over eastern Europe, that could act as a favourable preconditioning for wave breaking occurrence (Woollings et. al, 2006).The impression is that the there is good predictability in predicting the occurrence of wave breaking although the details might remain uncertain.

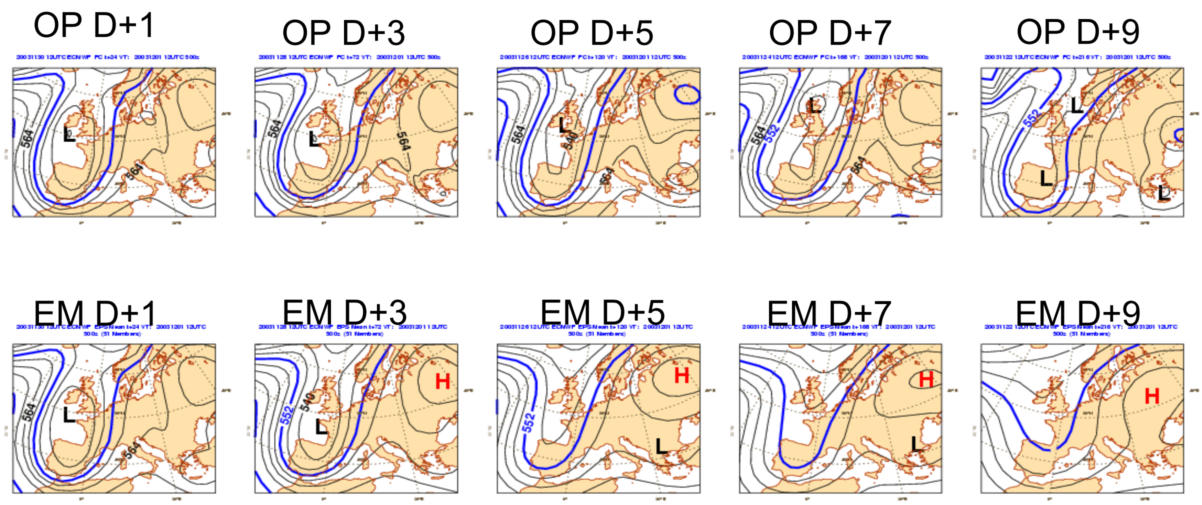

Figure 5: An example of forecast consistency for SSF conditions associated with the heavy precipitation and flood occurred 01 December 2003. On upper row are displayed operational forecast of 500 hPa Z verifying on 20031201 12UTC at different lead times. On the bottom row the same with the ensemble mean. Note the very high consistency of the forecast through the lead times for the deterministic forecast and the strong-consistent signal present in the ensemble mean.

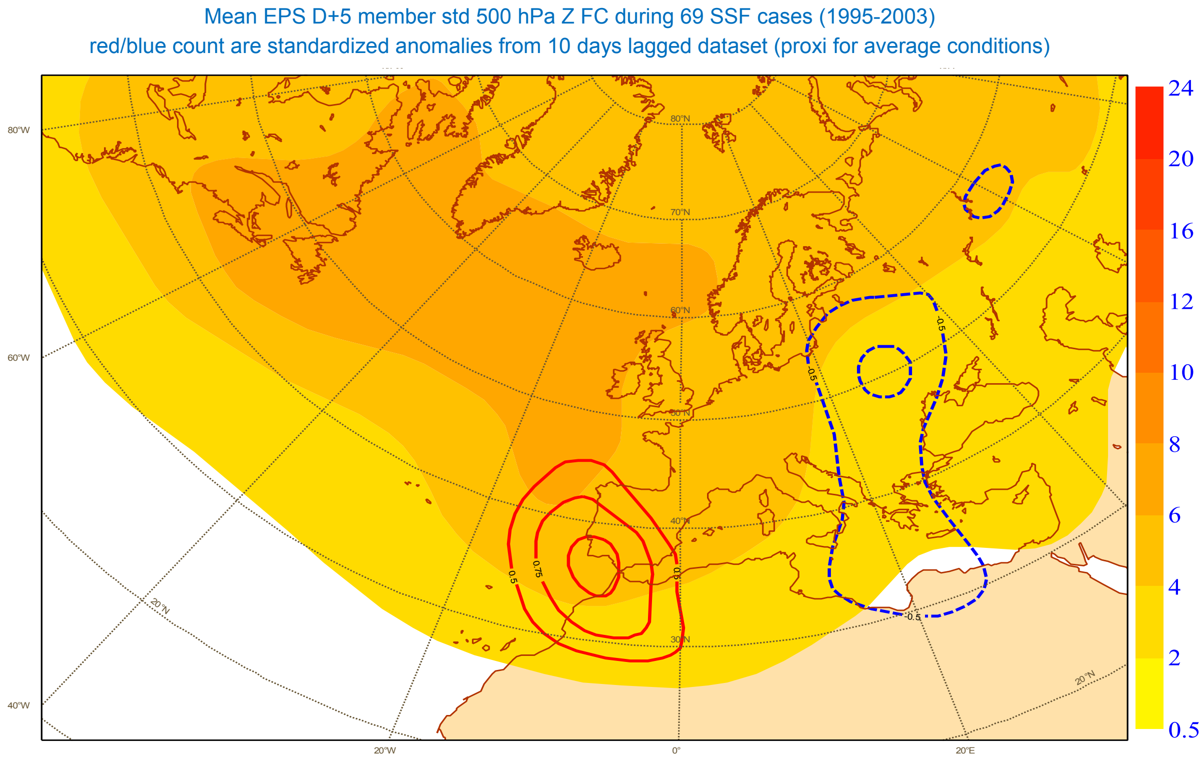

Figure 6: Composite of EPS D+5 standard deviation of 500 hPa Z over 69 SSF cases (1995-2003). Red/Blue contour are standardized anomalies respect to normal conditions

4. Predictability and Rossby wave packet

It has been shown that the wave breaking triggering SSF condition usually occurs at the end of a Rossby wave packet travelling from far upstream: in autumn the wave packet it is traceable back to the Pacific, in spring it originates over N-America (Grazzini, 2007). In the attempt to draw a more general picture on flow dependent predictability, we shall focus our attention to the ability to correctly predict Rossby wave train, seen as precursors of a wide range of meteorological activity, rather than individual regimes. This is also clearly stated in the in the Thorpex Science Plan: "*The skilful prediction of Rossby wave-train activity is often a requisite for forecasting the synoptic-scale setting within which smaller-scale, high-impact weather events evolve at forecast time ranges out to two weeks. Rossby wave trains are initiated by components of the flow, such as: i) downstream baroclinic development; ii) the interaction of extratropical flows with large-scale topography, e.g., the Tibetan Plateau; Greenland; iii) variations in moist tropical convective-heating associated with ENSO, MJO, and higher-frequency convective variability within the tropical oceanic convergence zones and monsoon regions. Other aspects of interest are: i) the establishment and maintenance of Rossby wave guides; ii) triggering of sub-synoptic scale features by individual synoptic waves within wave trains and their feed back into the dispersion of the wave train"* (Shapiro and Thorpe 2004).

The study of Rossby wave train is therefore crucial for understanding weather and climate and also factors that are limiting their predictability. Persistent spell of anomalous weather are often observed in conjunction with pronounced and long lasting Rossby wave train (Shapiro and Thorpe 2004, Martius et al. 2006, Chang 2005). Although the skill of extended range forecast (say beyond 10 days) is still pretty low, there are hints that pronounced planetary waves wave train episodes may bring in extra-predictability due to their inherent long space-time correlation. The downscale cascade of energy from the slow evolving planetary scale circulations can act in fact to organise the synoptic-scale and mesoscale flow that it ultimately producing high impact weather. Orlanski 1995 also noted how that during Rossby wave packet activity the main dynamical forcing are mainly determined by energy transfer from upstream systems. Studying the ability of the current forecasting system to reproduce the observed properties of Rossby wave train dynamics it will help to diagnose what prevent predictive skill to reach the intrinsic predictability proper to such a large-scale motion. A first step to proceed towards this type of process oriented understanding/diagnosis has been attempted by Grazzini and Lucarini (2009) with the definition a planetary wave tracking algorithm that allow to compute origin/decay, duration , mean velocity of individual packets as shown for example in figure 7.

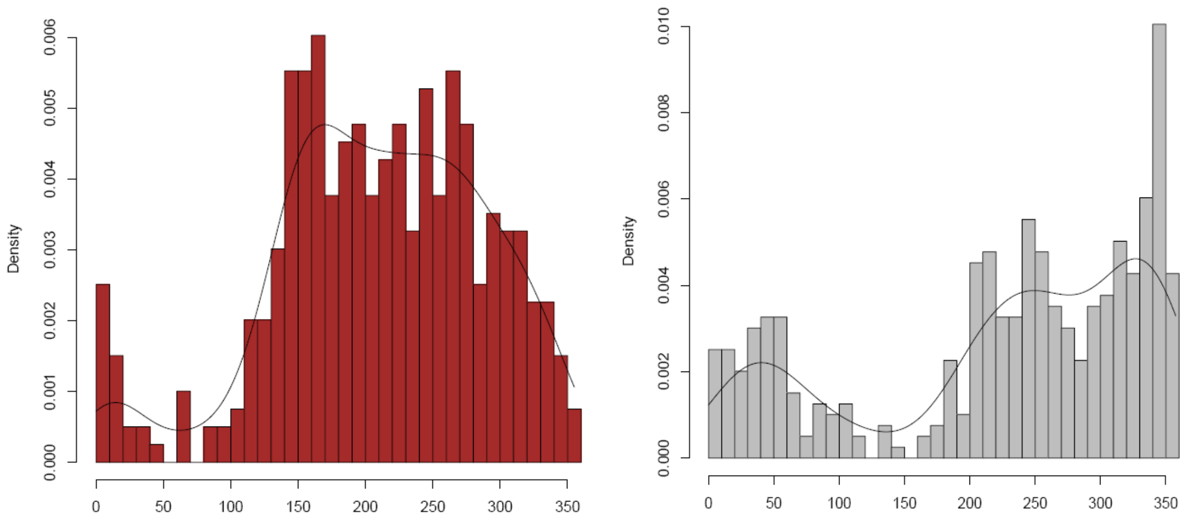

Figure 7: The left panel illustrates the distribution of the initial longitude of wave packets tracked by the algorithm in autumn months, in a band of latitude 35N-65N in the period 1958-2008 (from ERA40 plus operational analysis for recent years). The Western Pacific (130E-160E) clearly stands out as a preferential region for initiation of wave packets. The same but for the final longitude is shown in the right panel. Here the east Atlantic basin and Europe are identified as region where wave packets ends. Very little activity compared with other region it is observed over inner Asia. The envelope of v-250 hPa, on which is based the tracking algorithm, has been computed filtering on a zonal wavenumber between 4 and 8.

As seen in the figures that are referring to a long-term statistics computed over 51 autumn seasons, observed wave packet initiation has a maximum frequency over west Pacific, however all the Pacific basin, North-America and up to the east Atlantic are region of initiation. The north Atlantic sea and Europe are instead preferential regions for decay. Very remarkable is the very low propagation through the Asian continent. Mean velocities of the wave packet are in the order of 22°lon /day and the mean duration is about 4 days. These results agree fairly well with results find by Chung (1999) that has extensively studied Rossby wave packet propagation.

In figure 8 it is shown an example of wave packets identified in autumn 2008. It can be noted that, with the exception of a strong wave packet that formed 25/09 over west Pacific and reached the Atlantic on the 05/10, until the 20/10 the wave packet activity have been quite low implying a rather zonal circulation dominated by high frequency synoptic transient. After, it started a period characterized by the formation of long standing waves with wave packet travelling trough it (wp 6 and wp 7 in figure 8). We used these two periods, with clearly different circulation regimes, to investigate changes in skill and predictability.

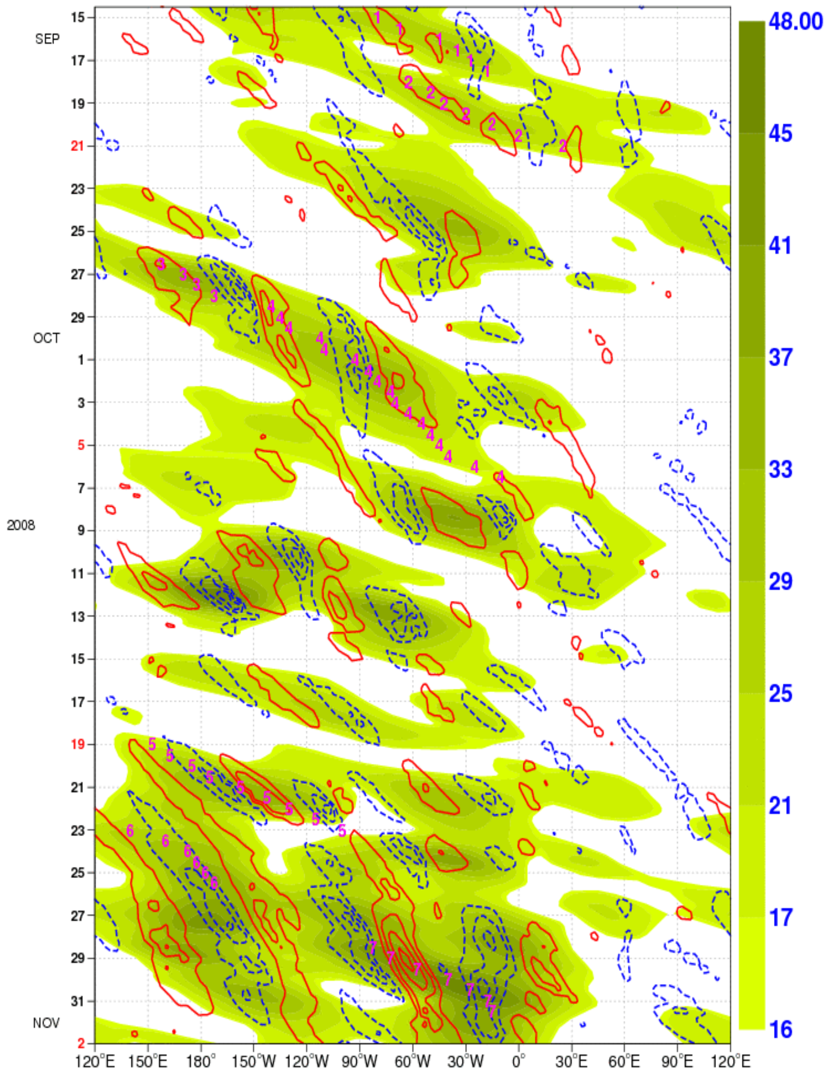

Figure 8: Hoevmoller diagram of v-component of wind at 250 hPa level (dash/negative, solid/positive, every 15m/s), envelope (wavenumbers 4-8) of the v-component of the wind at 250 hPa (shading m/s). Numbers represents individual wave packets tracked by the algorithm in the period 15/09 - 02/11/2008.

Figure 9 shows the predictive skill (solid line) and the potential predictability as defined by Lorenz (1982) (dash), based on MAE of Z500 over Europe, computed for two different periods of 15 days, one characterized by zonal flow, the other with long lasting Rossby wave packet activity. In the former period the error growth is very rapid in the medium-range, reaching a saturation level around D+8. The same behaviour is shown in the potential predictability curve that tend to converge to the solid line, indicating that predictive skill is likely to be limited mostly by very low predictability of the situation. In the latter period the trend of the curves in the medium-range is very different. In both curves there is a almost constant growth that seems to continue even beyond D+10, with a tendency to diverge. The slow growth of the dashed curve is suggesting that spells of high Rossby wave packet activity are periods in which atmospheric flow it is temporarily constrained, by the domino effect of inertia driven processes like downstream development, to assume only a limited number of states with a reduction of degree of freedom. In these conditions models errors can have a greater important, as indicated by the large difference by the solid line and dashed line. Given the higher predictability, in the hypothesis of perfect model we should obtain a greater reduction of the error. This may explain the greater reduction of error discussed above in case of SSF conditions.

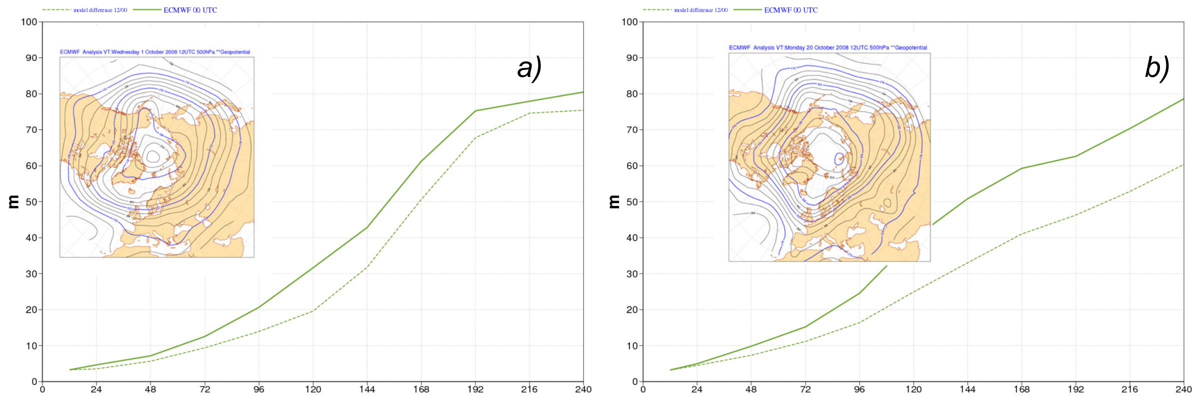

Figure 9: The left panel a) shows the growth of mean absolute error with the forecast lead time of Z500 computed over Europe in the period (01/10/2008 – 15/10/2008), period characterized by zonal flow (solid line). The dashed line shows the mean absolute difference of Z500, same period same area, between forecast initiated 12h apart and verifying at the same time (for example (fc+24 initiated at 00UTC) – (fc+12 initiated at 12h UTC) etc..). It is a measure of consistency of subsequent forecast. As suggested by Lorenz (1982) can be also taken as a measure of potential predictability. The dashed line therefore represent the best level of skill we could obtain for this atmospheric flow with an hypothetic perfect model. The inner panel shows the mean hemispheric Z500 flow during the period. In the right panel b) the same as in a) computed over the subsequent period 20/10/2008-03/11/2008 with high Rossby wave packet activity.

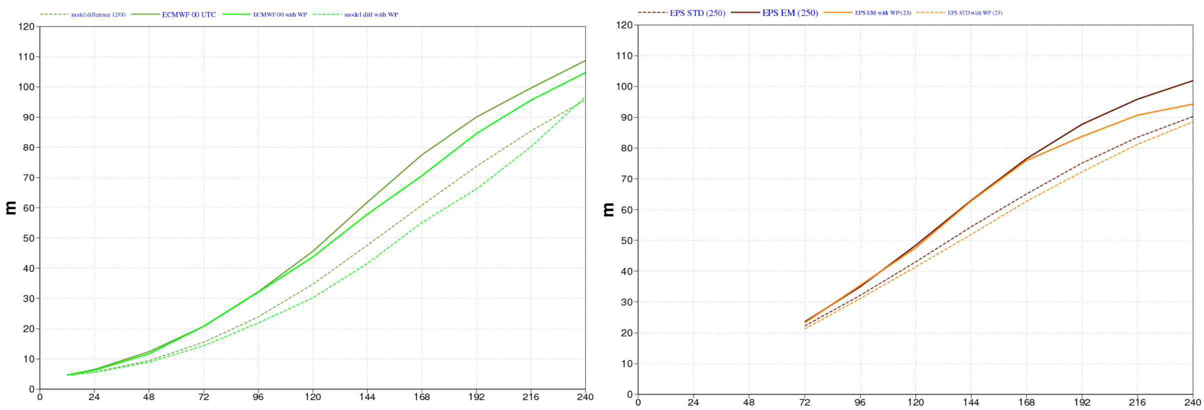

Figure 10: In this figure it is shown the sensitivity to the presence of wave packets in the initial conditions. On the left the dark green lines refers to RMSE of Z500, and potential predictability computed over (Europe+Atlantic) domain in the period 20080901-20081231. Light green lines refers to a subset (13) of cases of the same period with wave packet in the initial conditions. On the right the same with RMSE of EPS ensemble mean (solid) and spread (dash) computed over the same area for a longer period 20080901-20080531 (brown lines). Light lines refers to a subset of 23 cases of the same period with wave packet in the initial conditions.

A further test has been done comparing the scores obtained from forecast starting with the initial stage of a wave packet present in the initial conditions (as individuated by the Grazzini-Lucarini algorithm) with all other days (fig. 10). As can be seen from the left panel, predictive skill and predictability are lower when the initial stage of the wave packet is already present in the initial condition. A similar increase in predictability can be detected (although less clearly) in EPS system, in the right panel. With a wave packet in the initial condition (23 cases) the error of the ensemble mean and the spread are lower than other conditions. The reduction it is not so significant if the stratification is done by selecting cases with wave packet only at verification time (not shown), perhaps indicating that the predictability increase is maxima if the wave packet is contained in the forecast form the beginning. Once conditions are established for its propagations the model is reasonably able to maintain it, but its correct triggering might still result difficult since might require the correct parameterisation of physical processes, involving convection and diabatic processes, and the correct interaction with tropical modes (MJO for example) and stratospheric dynamics (Szunyogh et al.2008).

5. Summary and Outlook

We have shown that forecast accuracy is sensitive to different flow types.

Throughout the years the forecasting system has undergone numerous changes and improvements that have resulted in a overall continues increase in forecast skill. However, from a diagnostic perspective, it is perhaps more useful to investigate how system changes have projected on the ability to predict individual flow types or atmospheric states.

We have selected a local flow configuration, leading to strong southerly flow impinging on the south side of the Alps (SSF), and we have analysed the evolution of predictive skill in time. Model changes had a great positive impact on the forecast accuracy of SSF conditions, in particular those related with the handling of planetary waves.

SSF conditions are triggered by upper level wave breaking, often causing a decay of incoming Rossby wave packets (RWP) coming from upstream regions. Through the use of a new Rossby wave packet algorithm, we focused our attention onto the ability to predict wave packet evolution, seen as precursor of higher meteorological activity. Evidence were presented, indicating that spells of weather, characterized by an enhanced RWP activity, are more predictable (practically and potentially) than zonal conditions dominated by high frequency transient activity. In presence of high RWP activity remote regions of the atmosphere are more strictly connected by large-scale phenomena that presents long space-time correlation. Also ECMWF EPS estimate of predictability in RWP condition moderately support an increase of predictability.

We believe that objective RWP tracking could reveal to be a powerful tool for diagnosing core processes of large-scale dynamics like downstream development and RWP propagation in NWP and climate models. For example, in a recent paper Vitart and Molteni (2009) have investigated the teleconnections between MJO and European weather, as inferred from the ERA Interim reanalysis and by 46-day EPS hindcast simulations. RWP tracking could help to shed some light on the dynamics of this teleconnection, that appear to be present in the reanalysis. At the same time it might highlight model deficiencies that still prevent to achieve the correct strength of this teleconnections in the extended-range hindcast simulation.

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