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DATA DENIAL EXPERIMENTS FOR EXTRATROPICAL TRANSITION

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1. INTRODUCTION

Extratropical transition (ET) of tropical cyclones presents a significant challenge to numerical weather forecasts. Small uncertainties in sensitive regions around ET events can lead to large forecast errors. An important source of such uncertainties lies in the insufficient data coverage. Introducing targeted observations into the data assimilation in the vicinity of an ET event or in regions sensitive to fast error growth may have a notable value for a numerical forecast.

Numerous field campaigns have been conducted in recent years in which observations were collected in specific regions and their benefit for numerical forecasts tested. The impact of these observations was positive overall but small, with maximum error reductions in some specific cases of 10 - 15%.

In recent data denial studies at the ECMWF the sensitivity of forecasts of the atmospheric flow over Europe to targeted observations taken in the Atlantic has been investigated (Buizza et al., 2007; Cardinali et al., 2007). In these studies it was assumed that data denial experiments in sensitive regions give an upper bound on the expected impact that extra observations released in targeting campaigns would have provided that the characteristics of the added data are similar to those of the data denied. The sensitive regions were calculated with singular vectors (SV) verifying over Europe. During ET events an average forecast degradation of 13% in terms of the root-mean-squared error (RMSE) of the 500 hPa geopotential height over Europe was found. This impact was larger than the average impact of denial in SV regions when no ET events were present.

In this study data denial experiments are designed to investigate the value of additional observations for historical ET cases over the Atlantic. The effect of denying data in the vicinity of the center of the ET event in question, in order to account for the physical processes during ET, is compared to the effect of denying data in regions sensitive to error growth over Europe. This comparison should give information about whether the ET region itself or the dynamically active regions identified by extratropical SVs are more important for error growth over Europe.

For one specific ET case the effect of denying data in regions sensitive to error growth in the ET system was assessed. In addition, for this specific case the effect of data denial in separate regions important for the steering and the dynamic development of the ET, such as the outflow region, the upstream trough and the subtropical ridge, was compared.

2. THE EXPERIMENTS

The data denial experiments are conducted with the ECMWF Integrated Forecasting System (IFS) in its 32r3 version. We ran the 4D-Var data assimilation system which has a 12 hour assimilation window at the resolution T511L60 and only two minimization loops at resolution T95 and T159 were used.

Our experiments consist of omitting observations in specific regions such that the analysis is calculated only from the first guess, i. e. the short range model forecast, in these regions. The denial of observations was performed only over the ocean.

Eight cases of tropical cyclones undergoing ET in the North Atlantic between the years 2002 and 2007 were chosen (Table 1). In the first experiment (SVout) data was denied in regions determined by the leading extratropical SV (SV1) optimizing over Europe within an optimization interval of 48 hours (Fig. 1, green areas). For the second experiment (ETout) data was denied in rectangular boxes placed around the respective TC center at each analysis time (Fig. 1, yellow box). The TC center was determined by the local minimum of mean sea level pressure or by the local maximum of relative vorticity at 850 hPa if no distinct mean sea level pressure minimum was found. The boxes were enlarged following the growth in scale of the mean sea level pressure isobars of the deep pressure system during its transformation from a TC to an extratropical system. The third and control experiment (Ctrl) is equivalent to the operational forecast but calculated with cycle 32r3.

Table 1: Overview of the 8 ET events, the number of denial cases, i. e. analysis times from which all the forecasts are started, and the ET times.

ET event	Denial cases	ET time
Cristobal	18	2002080900
Fabian	14	2003090818
Irene	18	2005081818
Maria	16	2005091012
Helene	9	2006092418
Chantal	12	2007080106
Gabrielle	16	2007091112
Noel	11	2007110300

Helene (2006) was selected out of the 8 ETs and further denial experiments performed. Observations were denied in regions determined by tropical SVs targeted on TC Helene (experiment TCSVout) (Fig. 1, red areas). Note

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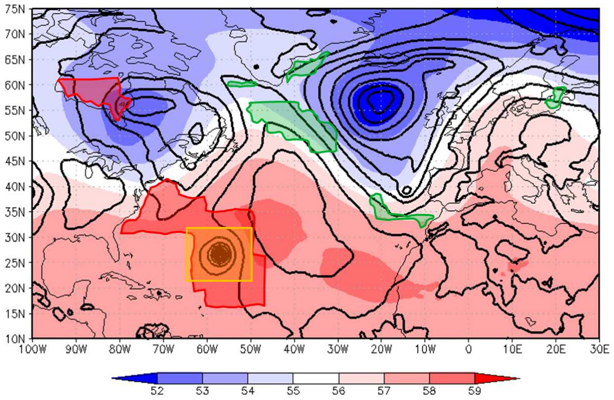


FIG. 1: ECMWF analysis during Helene's life cycle, i. e. on 21 September 2006 00 UTC, of 500 hPa geopotential (shaded) and mean sea level pressure (contours). Sketched denial regions for TCSVout (red), ETout (yellow) and SVout (green). Note that the denial was done only over the ocean.

that the SVout, ETout and TCSVout experiments are run cycled, i. e. with the exception of the first denial case of each ET event the background, which is the forecast from the previous analysis, has been modified by the data denial at previous times.

Further uncycled denial experiments are calculated for Helene. Rectangular boxes are chosen for the denial which encompass dynamical processes inherent in an ET. They are referred to as UTout (for 'upstream trough'), Oout (for 'outflow') and SHout (for 'subtropical high') (Fig. 2).

For all the experiments the impact of the data denial was determined using the 500 hPa geopotential root mean squared error (RMSE). RMSEs were calculated, first, between the denial forecast and the control analysis, and second, between the control forecast and the control analysis averaged over the European verification area (35 - 75° N, 10° W - 30° E). The impact is defined as the difference between these two RMSEs normalized by the RMSE of the control forecast. A negative impact indicates a degradation of the forecast if data are removed implying that adding observations in the denial region would possibly improve the forecast over Europe.

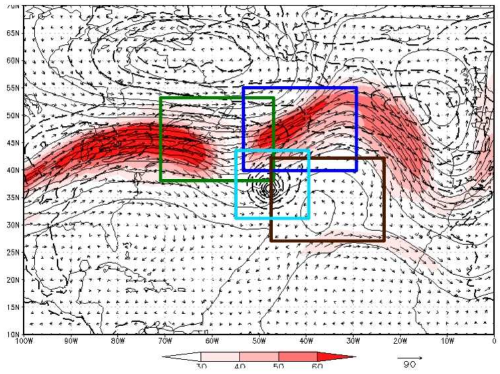


FIG. 2: UTout (green), ETout (turquoise), SHout (brown) and Oout (blue) box defined for 23 September 00 UTC. Analyzed 200 hPa geopotential (black contours), 200 hPa isotachs (shaded, ms^{-1}), 200 hPa wind vectors, mean sea level pressure $\leq$ 1010 hPa (dashed contours).

3. IMPACT OF ETOUT VERSUS SVOUT

The average impact due to SVout and ETout at every 12 hour forecast interval are shown for denial cases initialized before and after the ET time separately as well as for all denial cases together (Fig. 3).

The strongest impact due to SVout is at similar forecast lead times (36 h and 48 h) for data denial initialized both before and after the ET time (Fig. 3, top, middle). At the adjacent forecast intervals the impacts for SVout are rather strongly negative also. Averaged over all data denial times (Fig. 3, bottom) the strongest impact due to SVout, i. e. -6%, is at 48 hours.

In contrast, the strongest impact due to ETout averaged for data denial cases initialized before and after the ET time occurs at very different forecast lead times, i. e. about -6% at 120 hours for cases before ET and about -6% at 24 hours for cases after ET (Fig. 3, top, middle). Averaging over all the data denial cases cancels out these impacts such that the strongest impact of only about -3% is found at 12 hours and 120 hours forecast times (Fig. 3, bottom).

Obviously, when comparing the impact of ETout and SVout we must recognize that the extratropical SVs optimize after 48 hours over Europe and, hence, the strongest impact of SVout averaged over all denial cases is expected for 48 hours. In contrast, the strongest impact of ETout is not optimized for a certain time and so individual strong forecast errors are averaged out.

From these investigations it is evident that denial in ETout regions is at least as important as denial in SVout regions for a forecast degradation over Europe at assimilation times before the ET events. The strongest impacts due to ETout occur for longer forecast lead times as the denial regions are mostly close to the east coast of the United States and often still in the subtropics. Consequently, the impact takes more time to propagate across the Atlantic than that due to the SVout regions which are already in the midlatitudes and sometimes close to or over Europe. For data denial times after the ET events the denial in SVout regions yield slightly higher forecast degradations than denial in ETout. The strongest impacts are for short forecast intervals as the denial regions are closer to Europe.

To examine how large the impact due to ETout and SVout can get within a 5 day forecast, the strongest positive and the strongest negative impacts were investigated for each denial case (Fig. 4). Note that the forecast lead times at which the impacts are highest are in general not identical for all the denial cases.

The average over all the strongest impacts for each denial case shows that the values of the strongest negative impacts (possible improvement due to additional data) are

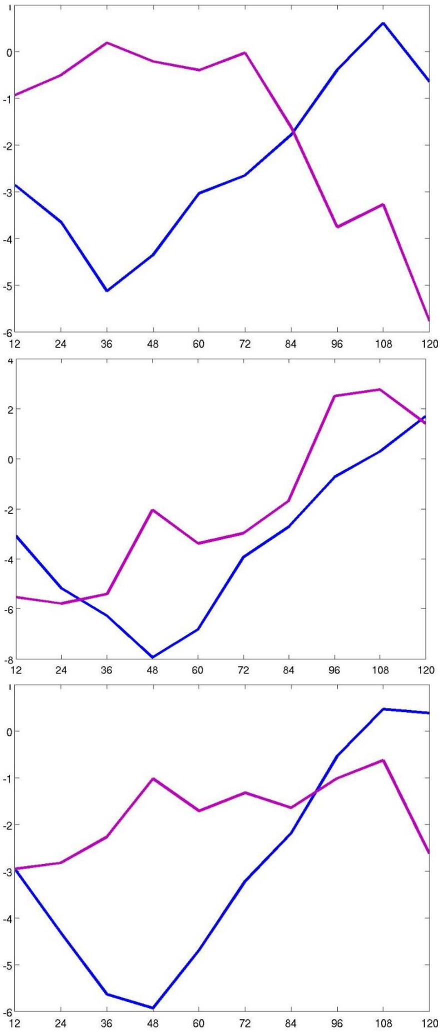


FIG. 3: Percentage impact for ETout (purple) and SVout (blue) for data denial cases before ET time (top), after ET time (middle) and for all data denial cases (bottom) over Europe.

distinctly higher than those for the strongest positive impacts (possible degradation due to additional data) for both SVout and ETout (not shown). Furthermore, both the negative and the positive impacts for ETout have higher values, i. e. -21.6% and 14.4%, than those for SVout, i. e. -19.2% and 12.9%.

Comparing the strongest negative impacts for SVout (Figs. 4, top) and ETout (Figs. 4, bottom) it can be seen that 12 data denial cases for ETout show degradations below 50% while for SVout only 4 denial cases with such high degradations can be found. Although a rather high part of the mean of the degradation in ETout can be attributed to Fabian, for almost every ET event one or more denial cases are seen which show stronger degradations in ETout than in SVout.

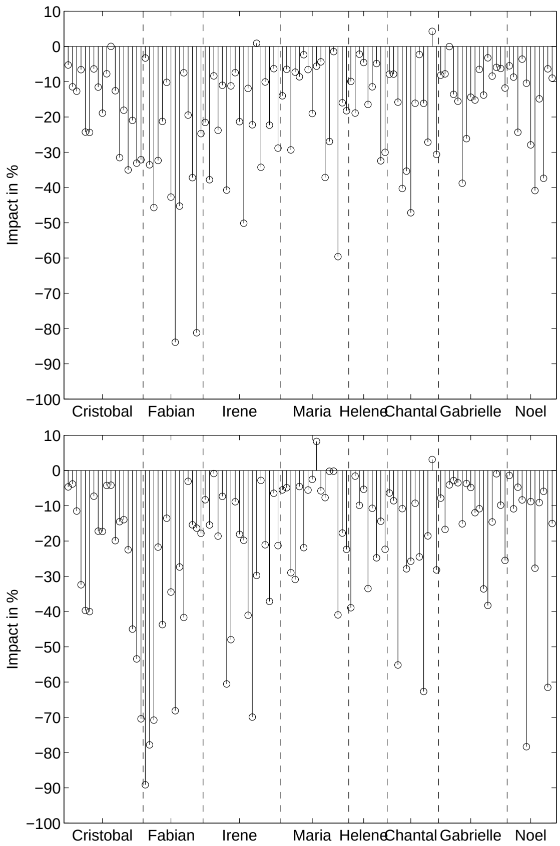


FIG. 4: Percentage degradation in 500 hPa geopotential height (m) at times of strongest impact for each data denial case. SVout (top) and ETout (bottom). ET events are separated by vertical dashed lines.

The strongest positive impacts for SVout and ETout are much more similar to each other (not shown). The maximum improvements are about the same and equally numerous for ETout and SVout.

Hence, larger forecast errors can be expected over Europe due to denial in the ETout boxes than due to denial in the extratropical SV regions. In contrast, forecast error reductions due to data denial are about the same for ETout boxes and for SVout regions.

4. THE ET OF HELENE

In order to investigate the role that the observation coverage plays in other features associated with an ET, in contrast to the processes close to the TC core, we selected one case out of the eight ET events. Hurricane Helene was chosen for our additional experiments because a distinct downstream trough formed over Europe during its ET, which developed to a cut-off low about 2 days after the ET time.

4.1 *Impact of ETout, SVout and TCSVout - cycled*

The SVs targeted on Helene are found in larger regions around the TC associated with the upstream trough, the subtropical high pressure system that steers Helene towards the northwest, as well as with the downstream midlatitude ridge. Hence, they not only include our ETout boxes but also describe other features important for the development and movement of the TC. Obviously, comparing the impact of ETout with that of TCSVout gives information about the importance of the processes close to the TC center relative to those in the regions farther away including those close to the TC center.

In Fig. 1 the locations of the TCSVout, ETout and SVout regions for the ECMWF analysis of 21 September 2006 00 UTC are compared. The ETout region (yellow) is covered by the TCSVout region (red). The SVout regions (green) are associated with instabilities in the midlatitude baroclinic zone. They do not overlap with the TCSVout regions for all the Helene cases until the 23 September 12 UTC (not shown). Hence, before that time they are not associated with error growth due to Helene.

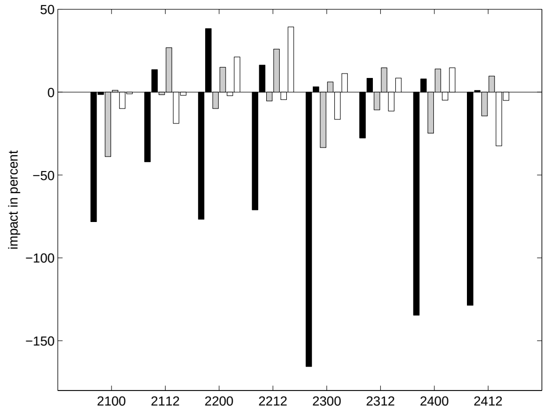


FIG. 5: Strongest negative and positive percentage impact over Europe for TCSVout (black), ETout (grey) and SVout (white) for the data denial cases for Helene.

Comparing the percentage of the strongest impact of data denial in TCSVout, ETout and SVout (Fig. 5) as in Fig. 4, it is obvious that for TCSVout the strongest impact for all the denial cases is negative and at least twice as high as the negative impacts for ETout and SVout. Considering, however, that the denial region for TCSVout is more than twice as large as that for ETout on 21 September 00 UTC (Fig. 1) the impact of ETout is notable. The impact due to data denial in the ETout box is as large as the impact due to data denial in the TCSVout regions excluding the ETout box as the negative bar in ETout is more than half as high as that of TCSVout on 21 September 00 UTC (Fig. 5). Hence, at this forecast time a good description of the processes close to the TC core is very important in order to reduce forecast error. For assimilation times from 23 September 00 UTC on, i. e. after the interaction of Helene with the midlatitude flow, the larger areas around the ETout box are much more important than the ETout box as the negative impact due to TCSVout is three to four times higher than that due to ETout (Fig. 5).

For ETout the strongest positive impact from 21 September 12 UTC to 22 September 12 UTC is higher than the strongest negative impact. As we cannot conduct a statistical analysis from 8 data denial cases we consider just the absolute amount of impact at these denial times. Thus, we assume that the positive impact gives us information on the regions in which small changes in the initial conditions lead to the highest forecast impacts over Europe, i. e. which regions are most sensitive to error growth over Europe for an indefinite forecast time within a 5 day interval.

Denial in ETout has about half as high an impact as denial in TCSVout, i. e. -42.1% in TCSVout versus 26.8% in ETout on 21 September 12 UTC and -71.1% in TCSVout versus 39.3% in ETout on 22 September 12 UTC (Fig. 5). Hence, before Helene becomes embedded in the midlatitude flow changing the initial conditions by denying data in the ETout box has a high impact on the forecast over Europe relative to the other features included in TCSVout. Thus, we concluded that a good description of the initial conditions in regions close to the TC center is especially important in the early stages of ET.

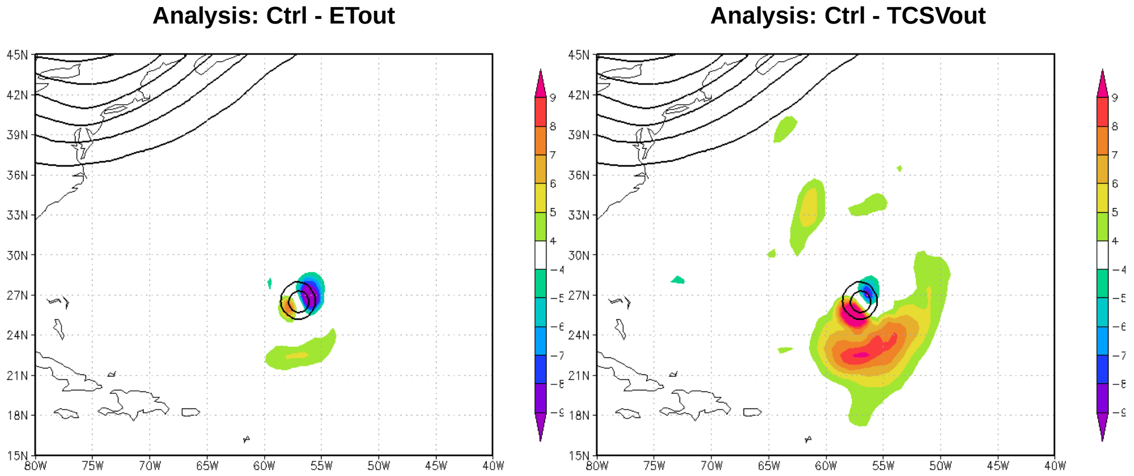
4.2 *Downstream propagation of Helene-errors*

For the data denial case of 21 September 00 UTC it will be illustrated how the error introduced into the analysis by the data denial in ETout and TCSVout propagates downstream towards Europe. The 21 September has been chosen as Helene was well south of the midlatitudes at this date which allows a good separation of the influence due to the TC from the influence due to the midlatitudes. Furthermore, it is the only data denial case for Helene for which the background is calculated from an analysis with the operational data set, i. e. without cycling. For both ETout and TCSVout the strongest degradation seen on 21 September 00 UTC (Fig. 5) is for a 120 h forecast (not shown).

A positive-negative couplet of height difference between the Ctrl and the ETout analysis is seen located on the northeastern and southwestern part of Helene's circulation indicating a shift to the northeast of the TC center in Ctrl compared to ETout (Fig. 6, left). A further small difference is seen directly south of Helene. The analysis differences between Ctrl and TCSVout show a very similar positive-negative couplet, but additional stronger positive height differences are found in a larger region to the south and east of the 500 hPa TC center and smaller scale positive regions are also seen to its northwest closer to the upstream trough (Fig. 6, right).

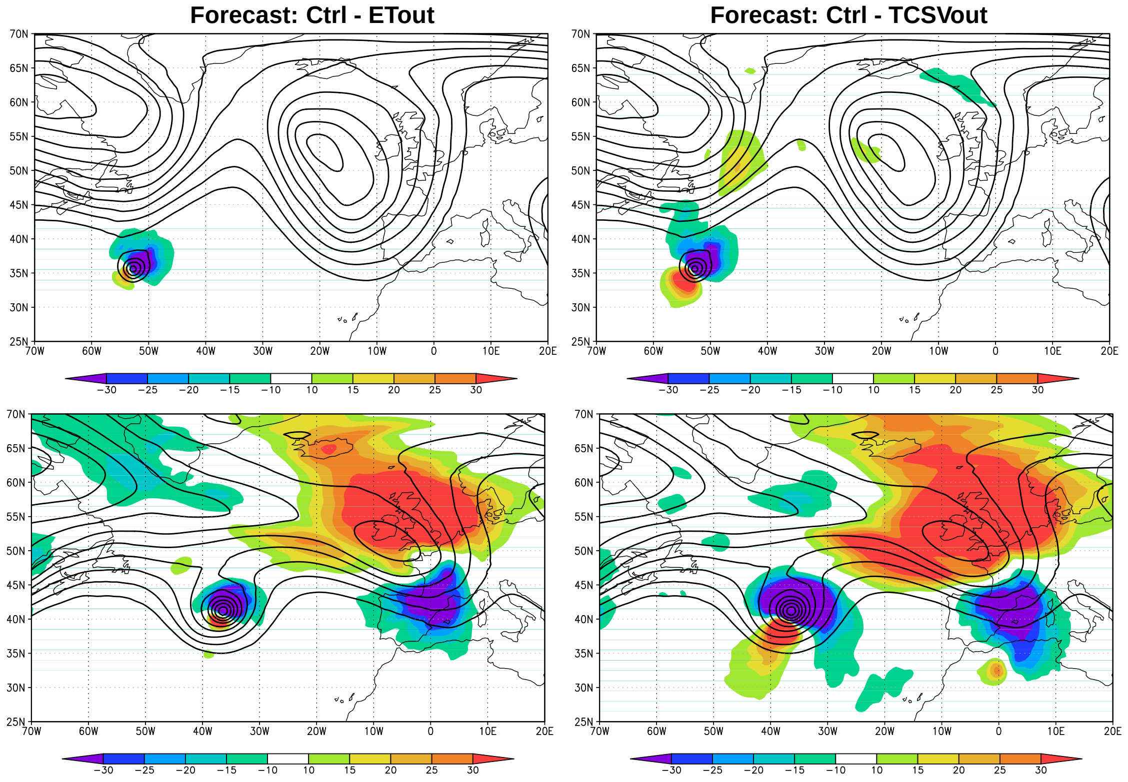
The forecast differences between Ctrl and ETout that develop from the analysis differences seen in Fig. 6, top left, show a deeper representation of Helene in Ctrl at 2 d (Fig. 7, top left). Differences between the Ctrl and TCSVout 2 day forecasts are associated also with a shift and a deeper representation of Helene in Ctrl (Fig. 7, top right). The differences in the midlatitudes east of Newfoundland originate from the upstream trough.

For the 4 day forecast, i. e. 6 hours after the ET of Helene was completed in the analysis, the difference between Ctrl and ETout has propagated from the ridge downstream into the low pressure system centered over the North sea (Fig. 7, bottom left). This low pressure sys-


Analysis: Ctrl - ETout

Analysis: Ctrl - TCSVout

FIG. 6: Analysis difference between the control and ETout (top), and the control and TCSVout (bottom) analysis of 500 hPa geopotential height (shaded, m) on 21 September 2006 00 UTC. 500 hPa geopotential height of the ctrl analysis (contours).


Forecast: Ctrl - ETout

Forecast: Ctrl - TCSVout

FIG. 7: Difference of 2-day (top) and 4-day (bottom) forecasts of 500 hPa geopotential height (shaded, m) initialized on 21 September 00 UTC between the control and ETout (left) and TCSVout (right). 500 hPa geopotential height of the ctrl forecast (contours).

tem is stronger and slightly further to the north in ETout than in Ctrl, connected to the more zonal flow in ETout compared to the flow with stronger ridging in Ctrl. In Ctrl the trough associated with the low pressure system digs further south towards the Mediterranean Sea. Ex-Helene deepened in both Ctrl and ETout, but the deepening in Ctrl is distinctly stronger, leading to the strong negative values (Fig. 7, bottom left).

The difference pattern between Ctrl and TCSVout (Fig. 7, bottom right) is similar to that between Ctrl and ETout. The deep pressure system centered over the North sea is slightly stronger in TCSVout than in ETout which explains the stronger positive values in its environment. Both in ETout and in TCSVout versus the Ctrl the trough over the Mediterranean Sea is weaker. The strong negative values in ex-Helene are due to the strong shift and comparatively weak representation of the ex-TC in TCSVout (Fig. 7, bottom right). In this experiment Helene did not deepen much after the 3 day forecast.

As in the previous section it is found that on 21 September the denial in ETout has quite a high impact on the downstream propagation of errors towards Europe. In TCSVout the differences originate partly from the upstream trough but to a big part also from Helene itself.

However, these results cannot be generalized for all the Helene data denial cases. In other cases, e. g. the 22 September 00 UTC (not shown), ETout does not show much difference to the Ctrl, whereas in TCSVout the differences propagate mainly from the upstream trough towards Europe and also towards Helene. Consequently, it would be of interest to examine how strong the degradation in other features associated with an ET, such as the upstream trough, can be and how such differences propagate downstream.

4.3 *Impact of UTout, ETout, Oout and SHout - uncycled*

To get further insight into the role the different ET features play for the forecast degradation the percentage impacts for UTout, ETout, SHout and Oout are compared for strongest positive and strongest negative impacts separately (Fig. 8).

For the 21 September 00 and 12 UTC the impact of ETout is highest, for 22 September 00 and 12 UTC the impact of UTout is highest. Hence, before Helene is embedded in the midlatitude flow, changes close to the TC core that determine its strength and exact position relative to the upstream trough or changes in the upstream trough that steers and interacts with Helene are more sensitive to error growth over Europe than regions which are located closer to Europe, such as SHout. In this stage, the description of the phasing between the TC and the upstream trough have to be exact because small changes can lead to a decay of the TC without interacting or to a very different ET development.

As Helene becomes embedded in the midlatitude flow on 23 September 00 (Fig. 2) and 12 UTC SHout and in particular Oout play the most important roles. In this phase, in which Helene is close to the strongest potential temperature gradient in the midlatitudes the outflow of Helene can be especially effective in changing the speed and the shape of the midlatitude jet. The modifications to the jet can lead to changes in the downstream trough over Europe. On 24 September 00 and 12 UTC all of the denial boxes have about the same importance.

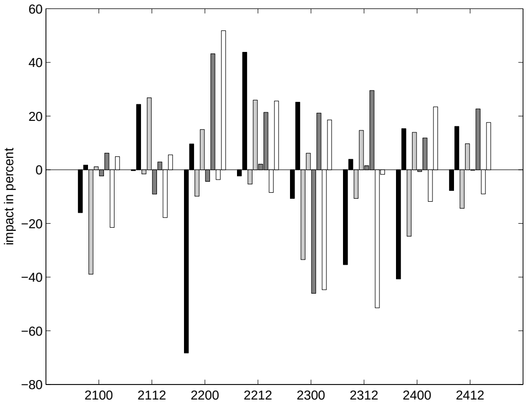


FIG. 8: Strongest negative and positive percentage impact over Europe for UTout (black), ETout (light grey), SHout (dark grey) and Oout (white) for the data denial cases for Helene.

From these investigations for Helene it cannot be concluded that one specific region has a particularly high impact on the forecast over Europe. Before Helene is embedded in the midlatitude flow the ETout region is quite important in comparison to the other boxes whereas the other boxes play a larger role during the later stages of ET. However, the SHout box can contain an important part of the TC core region. Thus, the impact of Helene itself is reflected in SHout as well.

It can be said, however, that for the case of Helene, regions associated with ET features are generally important. For two denial cases the positive impacts reach 40% or more and for 5 denial cases the negative impacts reach 40% or more. For every case one feature exists whose strongest impact is over 20%, which is distinctly higher than the strongest impacts of SVout for Helene (Fig. 5).

The downstream propagation of the impacts due to UTout, Oout and SHout was investigated for the data denial cases of Helene (not shown). For the data denial cases until 23 September similar behavior could be found. In most cases the Oout impact grows most quickly and arrives in Europe at the earliest time. However, in some cases quicker growth and propagation can be found for UTout. The impact of Oout has the largest scales at early forecast times, i. e. until 60 hours. The impact due to SHout, which is caused mainly by the regions close to the ET rather than by the subtropical high pressure system, arrives latest in Europe. The differences in SHout remain bound to Helene until the TC is close to the midlatitudes. From then on the differences start to propagate towards Europe. This behavior is similar to the differences between Ctrl and ETout (e. g. Fig. 7, left). After 23

September 00 UTC the propagation patterns and speed for all the boxes looks similar as they all propagate and grow in the midlatitudes.

5. CONCLUSION AND OUTLOOK

Based on these results it can be said that if weather centers aim for more continuous targeting during extreme weather events like extratropical transitions it is desirable to take into account the regions close to the TC center as well as the sensitive regions in the midlatitudes. In particular, during the propagation of a TC towards the midlatitudes additional observations around this system could improve the mid-range forecast over the downstream continent.

The experiments for Helene give an indication that a good coverage of regions sensitive for error growth on the TC undergoing ET yield by far the highest forecast improvement downstream. To confirm this, more studies of data denial in SV regions targeted on tropical cyclones are needed. Furthermore, the investigation of observation impact during other ET events in the different ET features upstream trough, outflow, and subtropical high pressure system should be performed. Finally, the investigation of other ET features, such as the enhanced baroclinic zone forming at the east side of an ET due to advection of warm and moist tropical air, or the investigation of denial in specific layers, for example the upper troposphere in the outflow region, are of interest.

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