TECHNICAL MEMORANDUM

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Evaluation of forecasts for hurricane Sandy

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Abstract

On 30th October 2012 hurricane Sandy made landfall on the U.S east coast with a devastating impact. In this report we evaluate the forecast performance from the ECMWF HRES and ENS forecasts together with ensemble forecasts from other NWP centres, available from the TIGGE archive. The results show that the ECMWF forecasts predicted the landfall 7-8 days in advance.

We investigate the impact of the warm SST anomaly outside the U.S east coast by running sensitivity experiments with climatological SST instead of persisting the SST anomaly from the analysis. We find that the SST anomaly does not affect Sandy's track in the forecast. However, the forecasts initialised with the warm SST anomaly feature a more intense system.

Furthermore we investigate the role of spatial resolution by comparing 4 different model runs, spanning from T3999 (5 km) to T159 (150 km) resolution. While all runs predict Sandy's landfall, at very high resolution the tropical cyclone structure and the the oceanic wave forecast is greatly improved.

Finally we investigate the impact of omitting data from polar orbiting satellites on the ensemble forecasts, and find that the data has an impact on the ensemble forecasts, although even without the data some ensemble members correctly predict Sandy's landfall.

1 Introduction

On the 30th October 2012 hurricane Sandy made landfall on the New Jersey coast with a devastating impact on New York City and its surroundings. The worst problems were caused by the storm surge leading to flooding including on lower Manhattan. Further inland the precipitation caused problems both due to the large amount and due to the fact that it fell as snow over high terrain. Earlier the tropical cyclone had severe effects in the Caribbean. A comprehensive investigation of hurricane Sandy and its impact is given in the report from the National Hurricane Centre (Blake *et al.*, 2013).

Making accurate and reliable predictions of extreme weather is a central objective in ECMWFs strategy. Sandy is an example of such an extreme weather event both in terms of its meteorological properties but also in terms of its societal impact. Whilst being classified as a hurricane through much of its life-cycle Sandy made the transition from tropical to extra-tropical storm status shortly before making landfall over the coast of the US. The impending "downgrading" of Sandy from tropical cyclone status just prior to landfall was a significant issue in attempting to keep the public focused on the dangers associated with the storm. For this reason the name "Superstorm Sandy" was introduced (by The Weather Channel) as a term that could be used throughout its life-cycle even after its extra-tropical transition and which emphasised its severity even after the transition. The landfall position of Sandy was extremely unusual, with only 2 similar landfalls on the northern U.S east coast in the past hundred years: the great New England Hurriance of 1938 and hurricane Irene in 2012. As a consequence of this and because of the severity of its impact on New York, the ECMWF forecast for Sandy received huge coverage in the US traditional and social media.

ECMWF has improved the skill of its tropical cyclone predictions over many years (Richardson *et al.*, 2012). It remains clear however that it is the performance of weather forecasts in individual high profile cases such as Sandy that can establish and retain the trust and confidence of the public and other forecast users; in a way disproportionate to their overall impact on average skill statistics. It is therefore of considerable interest to examine whether the predictive skill in such cases is sensitive to particular aspects of the forecasting system. In this report we assess the skill of operational models at predicting this weather system and investigate the sensitivities to some numerical and physical factors affecting this predictive skill. The focus is on the medium-range prediction of the landfall position in eastern U.S and not on the performance over the Caribbean. We compare both ECMWF high-resolution (HRES) and ensemble (ENS) forecasts and also forecasts from other forecasting centres, available from the THORPEX Interactive Grand Global Ensemble (TIGGE) archive (http://tigge-portal.ecmwf.int). We investigate the sensitivity to model resolution, sea-surface temperature anomalies and the impact of different satellite observations used in the data assimilation system.

We focus on the period leading up to and including the time of the landfall during which Sandy was classified as a hurricane for almost all of its evolution. Whilst ECMWF's forecasts for Sandy were generally of high quality there are many other cases where forecast skill is considerably worse in the sense that extreme weather exhibits predictive skill over only a few days ahead. Sandy seems to show a case of longer range skill and this provides further motivation to understand the factors that led to the predictive skill in this case.

2 Evolution of hurricane Sandy

In this section we summarise the evolution of hurricane Sandy. The intention is not to give a complete picture of the dynamics behind the cyclone, but to give the necessary background to the results presented in this report.

Figure 1 shows the development of the tropical cyclone in the analysis (mean-sea level pressure, MSLP) and the precipitation (during the first 6 hours of the forecasts). The origin of the system was in the Caribbean where the tropical cyclone first appeared on the 23nd October 00z in the analysis (Figure 1(b)). At 00z on the 22nd (Figure 1(a)), a convective system was present in the formation area. The storm moved northward and made landfall in Cuba and Haiti on the 24th.

After passing the Bahamas on the 26th October, the storm weakened and continued north-east over the western Atlantic. The cyclone started to deepen again and on the 29th October, the storm began to curve to the west instead of curving towards to the east as usual during extra-tropical transitions of cyclones (Jones *et al.*, 2003). The turn towards land was influenced by an interaction with a trough (see later in this section) and the connected cold air mass. The associated enhanced baroclinicity led to a rapid deepening of the cyclone the last day before landfall on the New Jersey coast with a minimum pressure in the analysis of 947 hPa.

Figure 2 shows the analyses of 200 hPa geopotential height (z200) and MSLP below 990 hPa from 2012-1023 00z to 2012-10-30 00z. The z200 parameter has been chosen as a proxy for the steering flow determining the path of the cyclone, at least after the cyclone has left the tropics. Studying the sequence of analyses from the 26th to 30th we see that the movement of the cyclone agrees well with the isolines of z200. During these days a ridge was amplifying over the eastern Atlantic and Sandy was moving northward of the western side of the ridge. The narrow ridge was ”squeezed” between a trough in the west and a cut-off low to the east.

The trough west of the ridge was propagating eastwards and strenghtening during this period (23-30th October). On the 23rd it was located over the north-eastern Pacific and on the 29th October the tropical cyclone start to interact with the cold air associated with the trough. The cold front connected to this trough is also visible in the precipitation maps on the 25th to the 27th, sweeping down over mid U.S (Figure 1). The ridge-trough structure is setting the scene for the dynamics involved in the landfall of Sandy.

As hurricane Sandy headed north roughly parallel to the US coast, further north the westerly upper level flow was disturbed with the significant trough over North America progressing eastwards. This trough

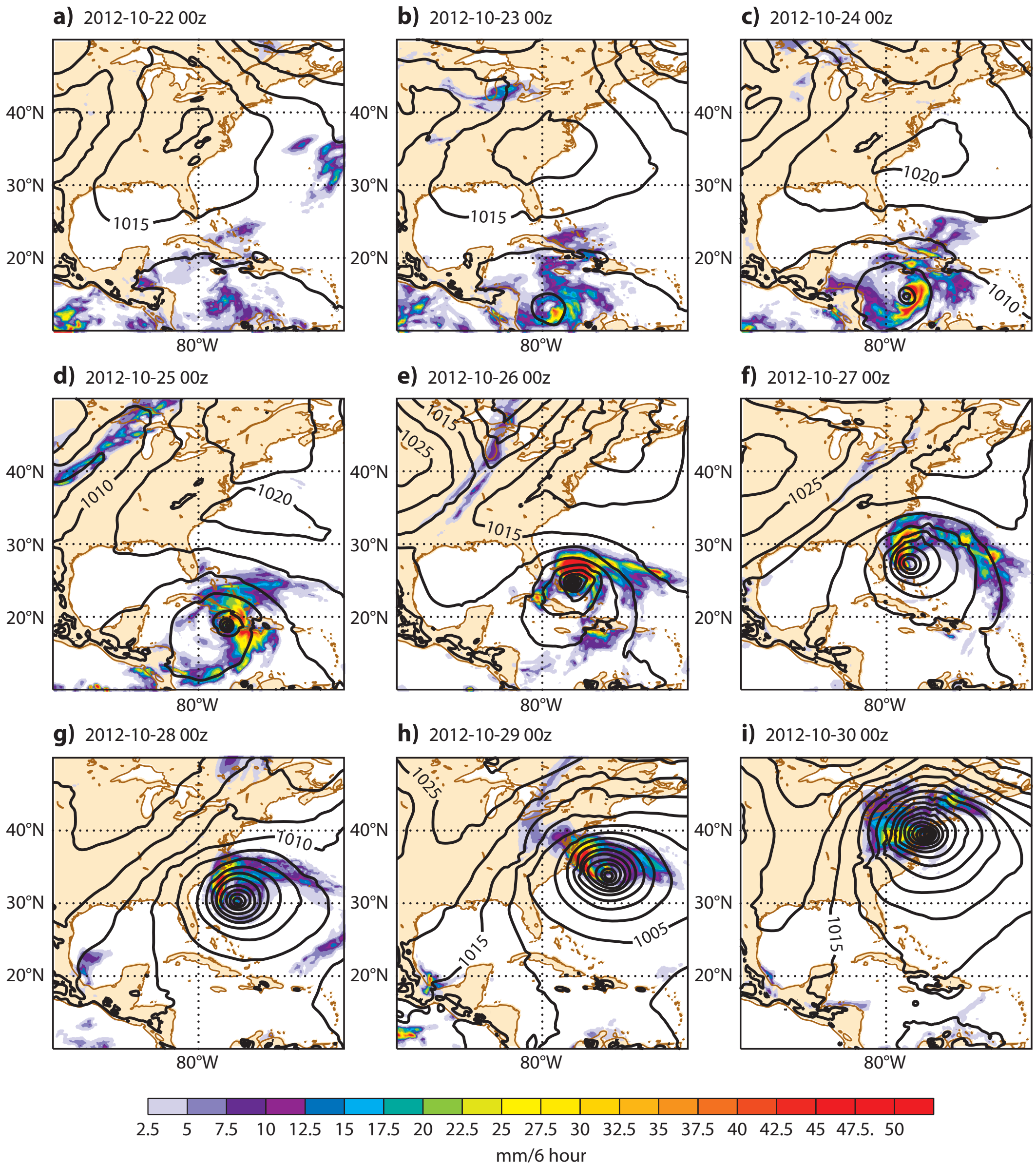

Figure 1: MSLP from the analysis and the precipitation accumulated during the first 6 hours of the forecasts.

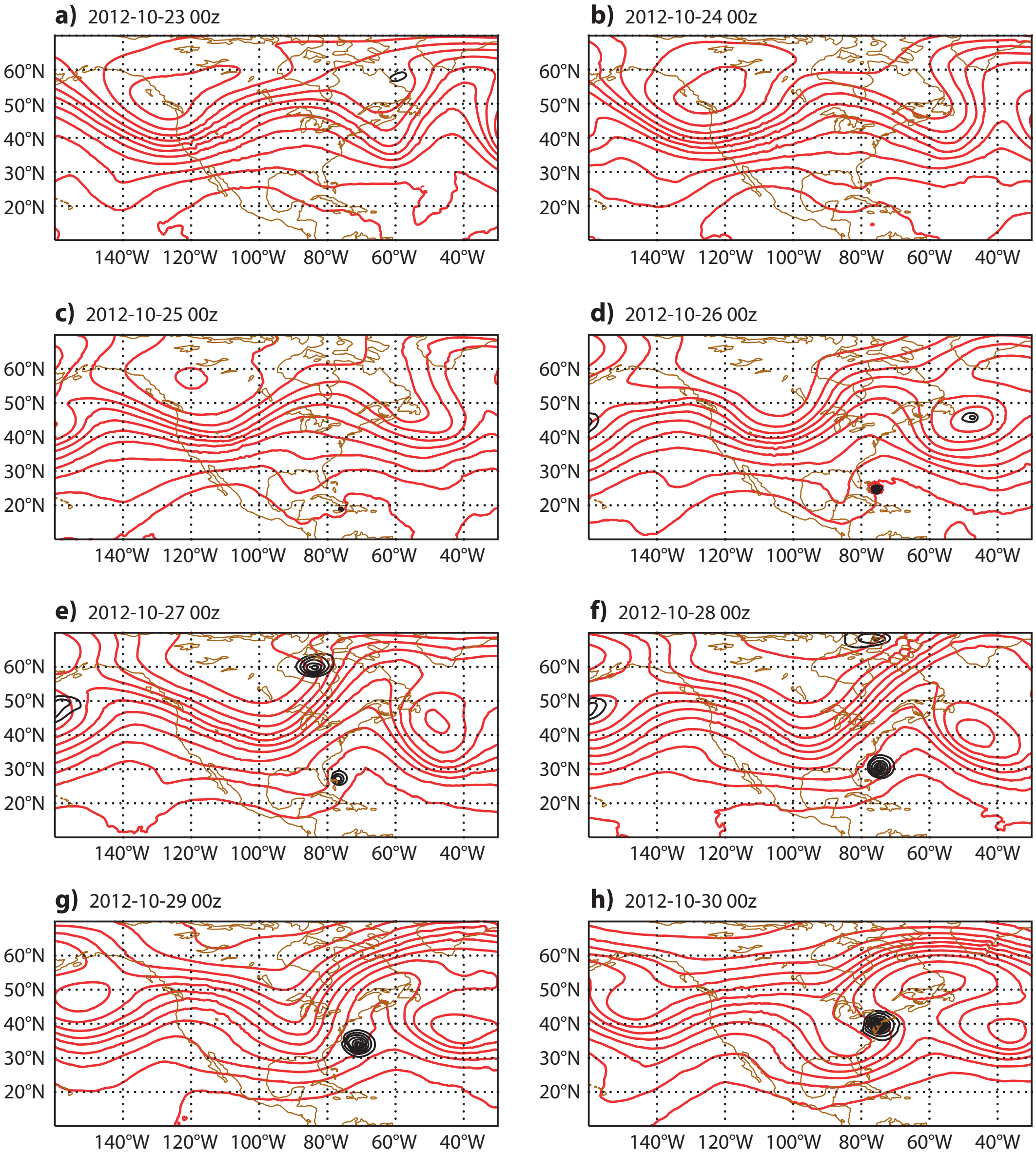

Figure 2: Analyses of z200 (red) and MSLP below 990 hPa (black).

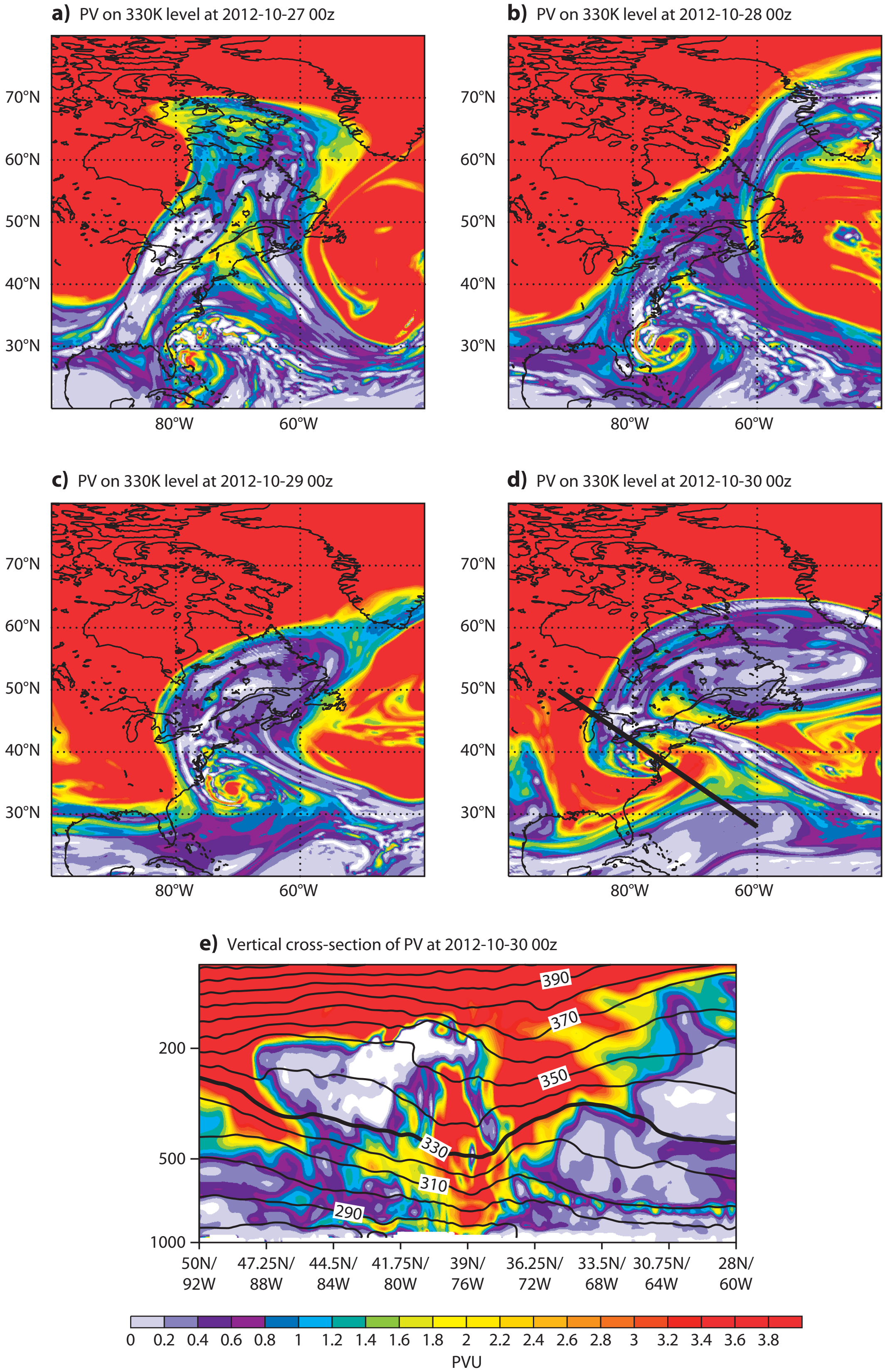

Figure 3: Analysis of potential vorticity.

was related to an eastward-propagating Rossby wave that can be traced back earlier over the Pacific Ocean (see Figure 2). It (hereafter ”the pre-existing trough”) evolved towards a (cyclonic) wave-breaking collapse somewhere near the east coast of North America. During the last day before landfall, Sandy was making a transition from being a tropical cyclone to having a more extra-tropical storm structure. Such transitions in previous storms have been the subject of extensive research (Jones *et al.*, 2003).

The interaction between Sandy and the trough is now analyzed further by looking at the evolution of potential vorticity (PV). Figure 3 show the potential vorticity analysis from the 2012-10-27 00z (a) to 2012-10-30 00z (d) on the 330 K level and a vertical cross-section (e) spanning from 50N/92W to 28N/60W for the 2012-10-30 00z. The 330K isentropic surface is typically in the troposphere in the warmer tropical air-masses to the south whilst it is located in the lower stratosphere further north. In frictionless flow the PV (and θ) is conserved by air parcels and therefore PV is a good indicator of air trajectories; see Hoskins *et al.* (1985). By way of contrast, anomalies of PV within air-masses can exist if there has been strong latent heating (or surface frictional processes). In extra-tropical and tropical cyclones the strong vertical motion and cloud and rain formation often leads to lower troposphere positive PV anomalies and upper-troposphere negative PV anomalies. In fact local anomalies of PV are often very good indicators of the presence of and dynamical significance of such diabatic processes; see local blob of high PV in Figure 3(a) and 3(b) indicating Sandy’s core location.

As Sandy heads north, a large plume of tropical-origin low-PV air at upper levels expands northwards and zonally (with an eastern lobe heading over the Atlantic and a western lobe heading westwards over the US landmass, see Figure 3(c) and (d)). This plume has the appearance on 2012-10-30 00z of a quasi-horizontal “mushroom cloud” of tropical warm low-PV air spreading out. The eastern lobe of the mushroom rolls up anti-cyclonically as might be expected given that it comprises low PV. However the western lobe wraps up cyclonically over the pre-existing trough (indicating that in that location the tropopause is significantly folded over). The trough can be seen to the west in Figure 3(c) and Figure 3(d). At this stage the trough has the low PV plume located directly above it and, arguably, forces the low PV plume to wrap-up cyclonically (possibly against its natural tendency to wrap-up anti-cyclonically). The pre-existing trough at this stage is undergoing a (quasi-horizontal) cyclonic wave-breaking. This acts to “capture” Sandy and draw it further west toward the coast.

In Figure 3 a vertical cross-section is shown that cuts across from north-west to south-east at around the time of the landfall of Sandy; the figure shows isentropic surface contours and the PV in coloured shading. Several features are of interest and dynamical significance. The first is the existence of a tower of extremely high (and anomalous) PV in the troposphere located at the centre of Sandy. This is related to the strong latent heating of the air in that region. At this time this tower is essentially vertical although there is some evidence of it beginning to tilt towards the west with height which would be typical of the storm undergoing an extra-tropical transition. Above the tower in the upper troposphere there is a region of extremely low (even negative) PV also related to the consequences of the latent heating. This low PV is what is left at this time (near the centre of the storm) of the previously-mentioned mushroom cloud.

In this section we have described the evolution and features of hurricane Sandy and the processes needed for the track to be forecast correctly. Two important ingredients are the evolution of the ridge over eastern Atlantic (that steers the storm northward) and during the last day the interaction with the pre-existing trough that steers the storm westward toward the coast.

3 Operational forecasts

In this section we investigate the predictability of the hurricane in the operational forecasts (HRES and ENS) from ECMWF and other forecasting centres. The forecast performance is also discussed in Hewson (2012). We will also compare the results from other forecasting centres available in the TIGGE archive.

Figure 4 shows the MSLP for ECMWF HRES forecasts from 2012-10-21 00z to 2012-10-29 00z. All the forecasts are valid at 2012-10-30 00z, the time of the landfall on the New Jersey coast. The figures also includes the cyclone track from the analysis (red) and the forecasts (blue) together with a symbol for the cyclone centre at landfall time (hourglass symbol for analyses, square for forecasts). The colour of the centre symbol represents the depth of the centre.

The HRES forecast issued 9-days before the landfall had a cyclone over the Atlantic but on an eastward track that did not lead to landfall [Figure 4a]. The forecast from one day later (2012-10-22 00z, Figure 4b), was predicting a landfall very close to the observed landfall, but 12-hours too late. The forecast issued 2011-10-22 12z (7.5 days before landfall, not shown), had the storm two days too late and it made landfall too far north close to Boston. From 7 days before the landfall and onwards, the storm was consistently forecast to made landfall, with the main uncertainty in the timing of the landfall. The forecasts from the 25th and 26th had the landfall point somewhat too far south, but with a good timing.

Whilst the HRES forecast gave a reasonably consistent picture from about 8 days prior to landfall, the forecaster needs to know the degree of confidence one could have in such a forecast. The ENS forecast provides an estimate of the confidence by examining the spread among the ensemble members.

Figure 5 shows tropical cyclone strike probability maps (left panel) and cyclone minimum pressure (right panel) for forecasts initialised 6 days (24th 00z) and 4 days (26th 00z) before the landfall. The results are obtained from the tropical cyclone tracker described in Vitart *et al.* (1997, 2003). For the forecast initialised 6 days before landfall we see a spread among the ensemble members; some of the members curve eastwards and do not make landfall. The forecast from 4 days before landfall shows a much more confined ensemble although a few members take a more northerly track making landfall on the Canadian coast. Studying the pressure minimum (right panels) for the forecast from the 26th, we see that the HRES forecast (thick, solid) starts to weaken earlier than most of the ensemble members, indicating an earlier landfall. Also the depth of the cyclone is better captured by the HRES forecast. Note that the forecast from the 24th clearly miss the minimum pressure around the 25th when the cyclone makes landfall over Cuba.

In order to illustrate the ensemble forecasts in terms of the depth and position for each member, the position of the cyclone centre (Figure 6) for each ensemble member (squares) is plotted together with the control (triangle). The colour and size of the symbols indicate the depth of the cyclone centre (as in Figure 4). The position is defined as the local minimum in the forecast closest to the position in the analysis (hourglass symbol). In the figures also the cyclone track from the analysis (red) and the control forecast (green) is plotted. For the ensemble members a segment of the track is plotted covering for 12 hours before to 12 hours after the observed landfall time (grey). The figures in the left column contains forecasts from ECMWF and the right from NCEP. The ECMWF ensemble has 50 members while the NCEP ensemble has 20 members.

For the forecast from 2012-10-23 00z (7 days before landfall), the control forecast from ECMWF made landfall somewhat too north and 12 hours too late, a result consistent with the HRES forecast. The ensemble members are divided into two main groups: the vast majority of the members are on a track to make landfall, while around 10 members are on a eastward track towards the mid-Altantic. For the NCEP forecast, both the control and the main part of the ensemble are on the eastward track, while only

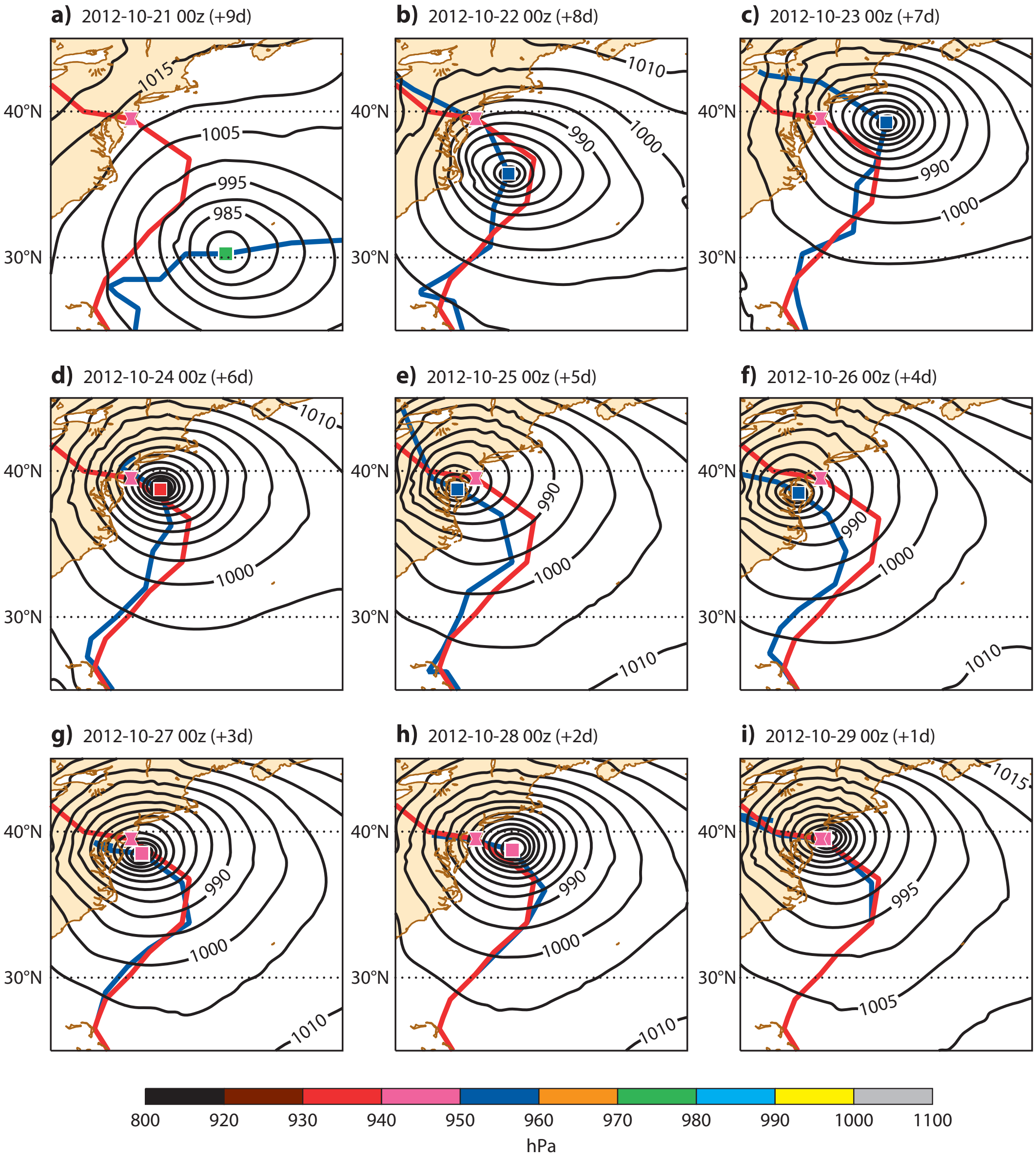

Figure 4: MSLP from HRES forecasts valid at 2012-10-30 00z and the cyclone track for the forecasts (blue) and the analysis (red). The position of the cyclone centre at 2012-10-30 00z marked as hourglass and the forecast with square. The colour of the symbol represents the depth of the cyclone centre.

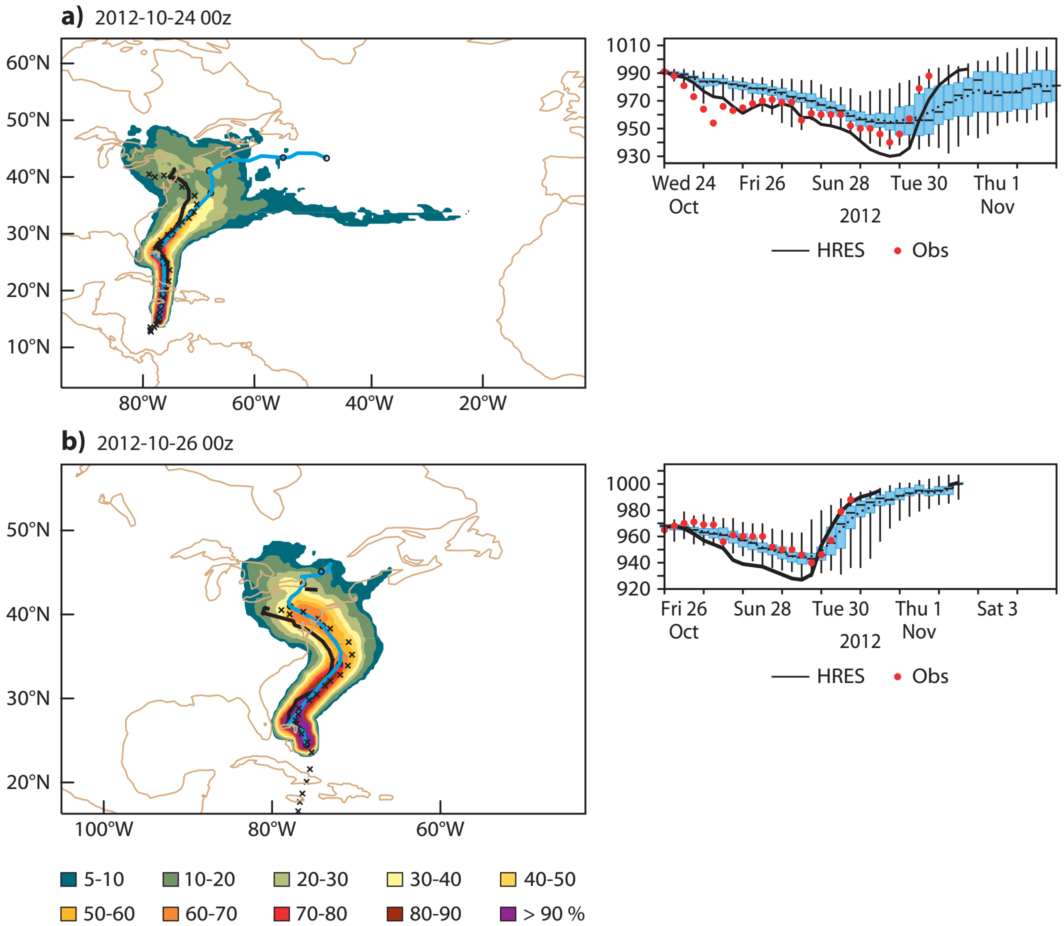

Figure 5: Strike probability map and minimum pressure (hPa) for the operational ENS forecast. HRES forecast track (black line) and mean position from the ensemble (blue line).

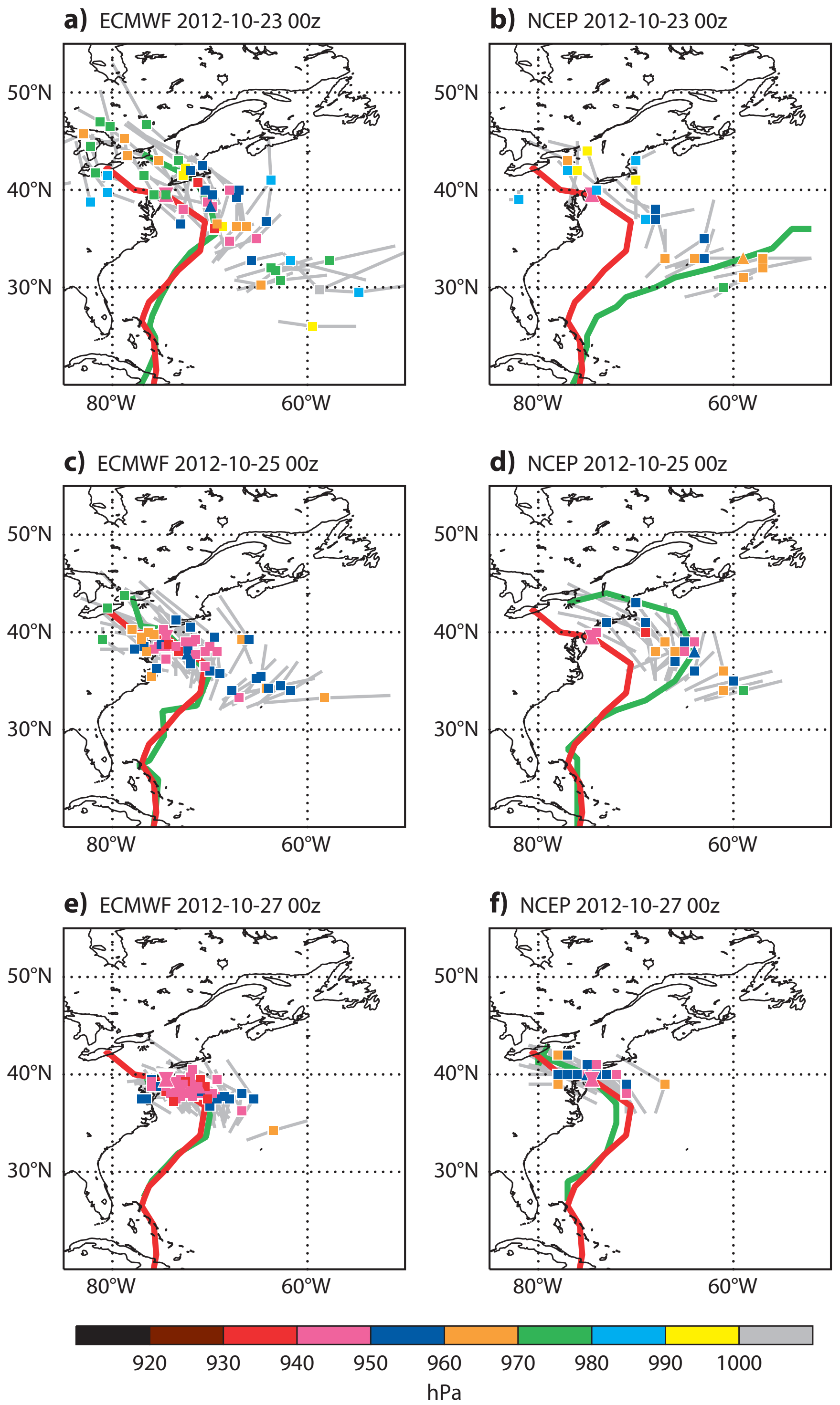

Figure 6: Forecasts from ECMWF Operational ENS. Position of the cyclone centre closest for the landfall position in ensemble forecast (squares) including the trajectory for -12 hours to +12 hours (grey lines). Cyclone track from control forecast (blue) and position at 2012-10-30 00z (triangle symbol). Landfall position in hourglass symbol and the observed cyclone track (red). Forcasts from ECMWF (left) and NCEP (right).

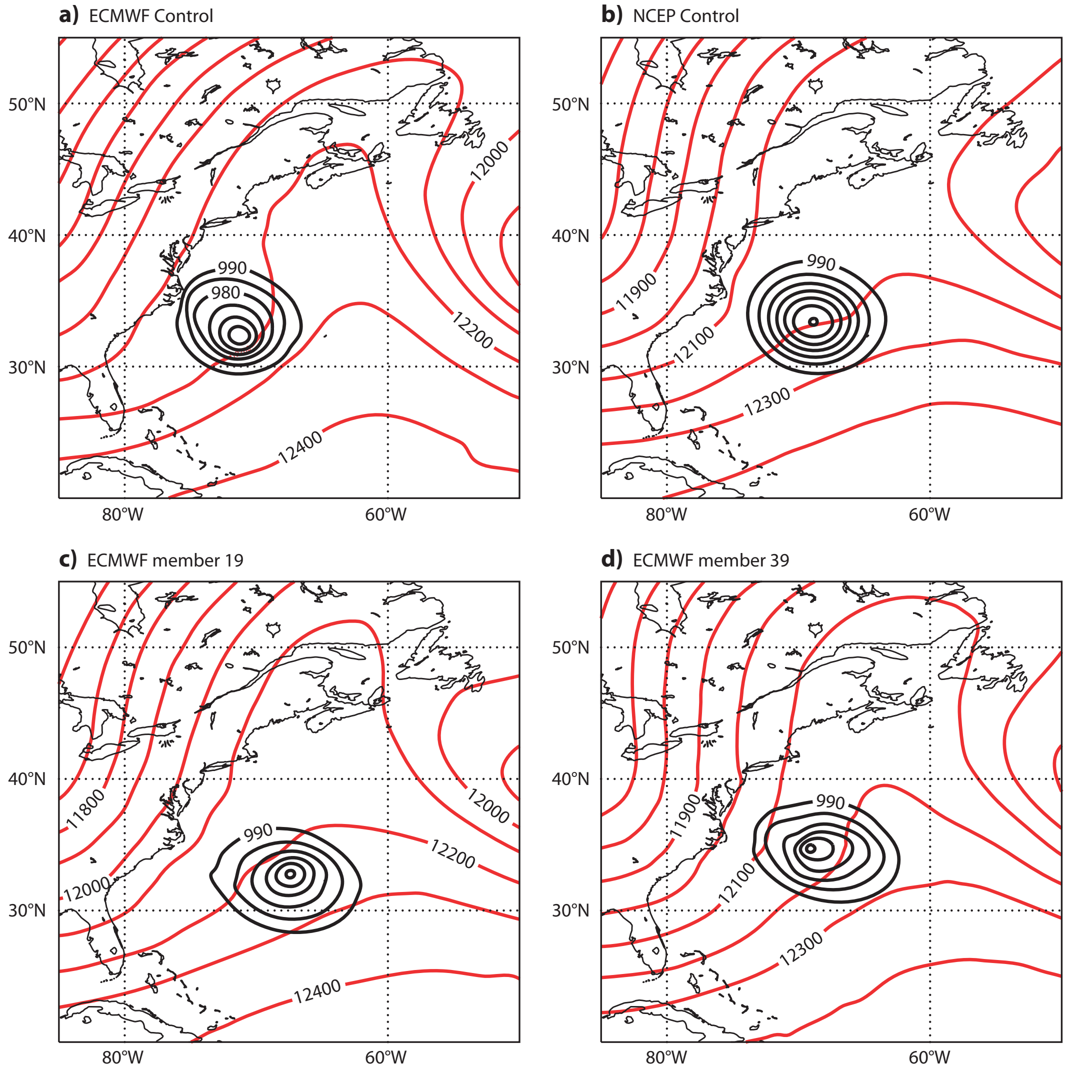

Figure 7: Forecasts of z200 (red) and MSLP below 990 hPa (black) for 2012-10-25 00z + 96h (1 day before landfall).

a few members correctly forecast the landfall on the U.S coast.

The ECMWF control forecast from 2012-10-25 00z (5 days before landfall) shows an almost perfect track but with a landfall 12 hours too late. A clear majority of the ensemble members are also on a similar track but showing a spread both in landfall position and timing. The eastward track is not eliminated here as well as a few members are on the northerly track. For the NCEP forecast this northward track is dominating, including for the control forecast. Only a few members predicted a landfall south of Long Island. Also NCEP had a few members going on the eastward track for this initial date.

For the forecasts from 2012-10-27 00z, the ECMWF ensemble has essentially all of the members on a track similar to the observed one, although most of the members show a timing error with the landfall 12 hours too late; there is 1 member (out for 50) on the eastward track. For this 3 day forecast, the NCEP ensemble seems better, with a timing error compared to the ECMWF ensemble.

In order to study the differences between the ECMWF and NCEP control forecasts and two ECMWF ensemble members on the wrong track, Figure 7 shows z200 and MSLP for pressures below 990 hPa

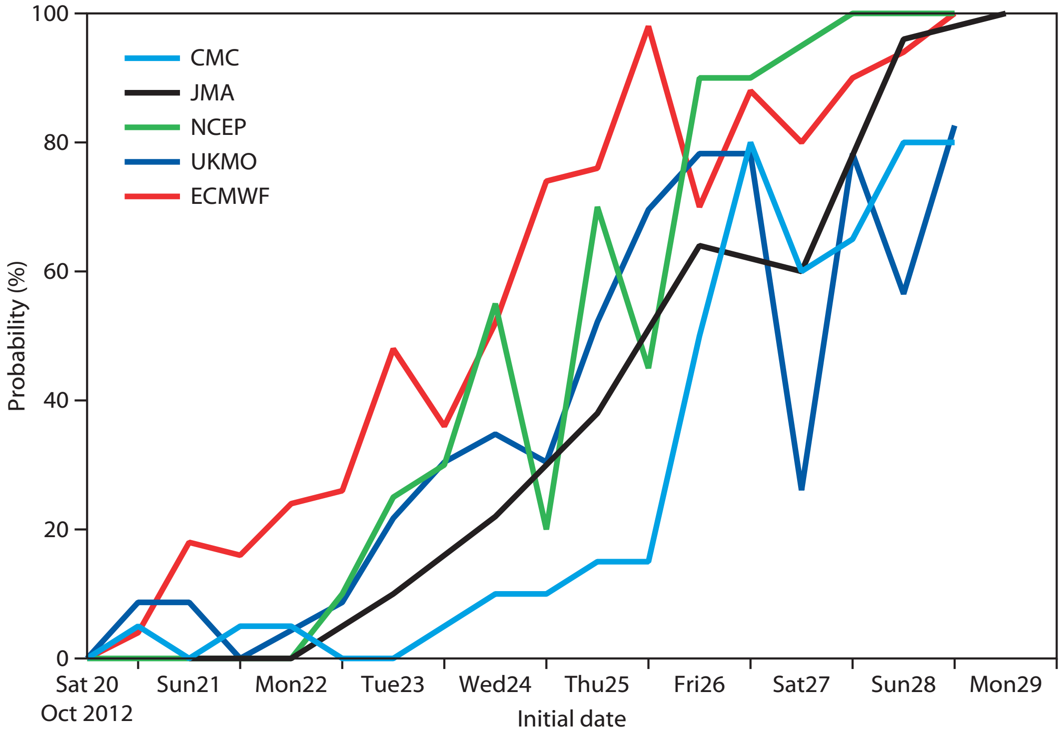

Figure 8: Probability (in %) of 850 hPa wind speed greater than 38 m/s somewhere inside a radius of 100 km for New York Harbour between 2012-10-29 12z and 2012-10-30 12z.

for forecasts from 2012-10-25 00z, valid at 2012-10-29 00z (one day before landfall). For this initial time the ECMWF control forecast had a good track while NCEP control had a too northward track. The ensemble member 9 (c) was the worst ECMWF member with the most extreme eastward track, while ECMWF member 39 had a track very similar to the NCEP control forecast.

Comparing the ECMWF control with the other forecasts plotted here, it had the strongest ridge to the east and the tropical cyclone had a northward track. For the worst member (member 9), the tropical cyclone was too far south and follows the isolines towards the east. The NCEP control and Member 39 are still moving north but with an eastward component, leading to a too eastward position when the interaction with the trough began. To conclude, the difference in z200 seems to explain the differences in the tracks.

Figure 8 shows the probability calculated from the ensembles (as the fraction of members fulfilling the criterion) of 850 hPa wind speed greater than 38 m/s somewhere inside a radius of 100 km centred outside New York Harbour (the area plotted in Figure 9) between 2012-10-29 12z to 2012-10-30 12z (in order to allow a timing error). The motivation for verifying the 850 hPa wind speed instead of the surface winds is to avoid differences in the influence of the surface between the different models. The 850 hPa wind speed in the ECMWF analysis is plotted in Figure 9, where we see that the condition is fulfilled in a wide area and mean windspeeds in excess of 44 m/s exist. The x-axis in Figure 8 represents the initial date of the forecasts. For short lead times the probabilities of the event are close to 1 and for long lead times close to zero as the climatological probability for the event is very small. The results are plotted for the ensembles from ECMWF (red), NCEP (green), UK Metoffice (blue), CMC (light-blue) and JMA (black).

The results show that for short lead times (up to three days before), NCEP (green) has the highest probabilities for the event. The results are in line with the visual inspection in Figure 6, indicating a better

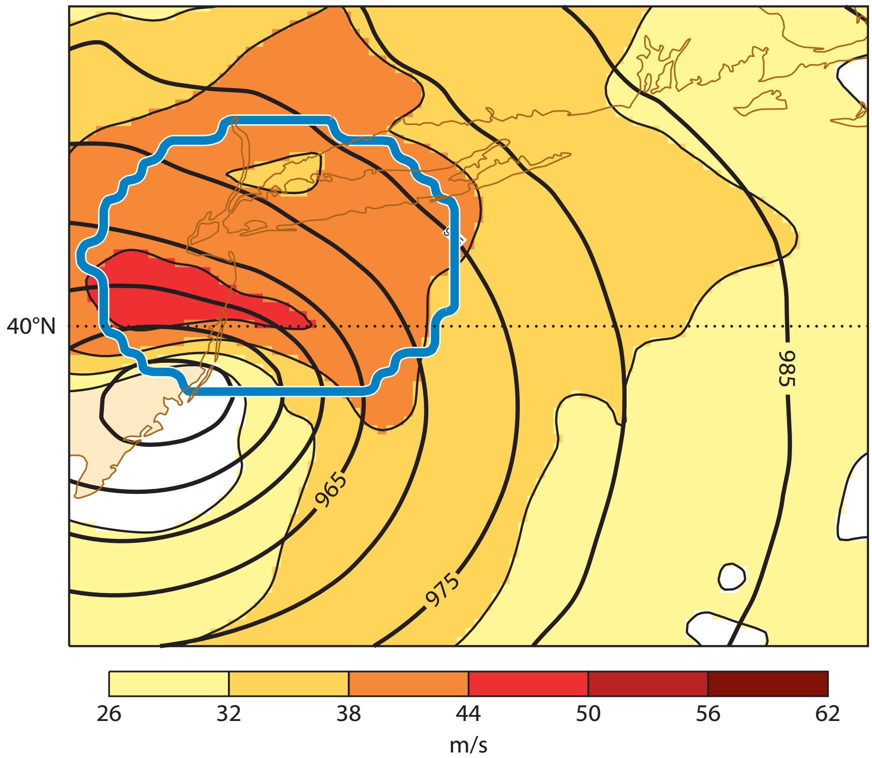

Figure 9: 850 hPa wind speed (shaded) and MSLP (thin, black) from the analysis from 2012-10-30 00z. The area for used for detection of the 850-hPa wind event (thick, blue).

performance for NCEP compared to ECMWF. Already for short lead times the UK Metoffice ensemble shows relatively low probabilites. This is due to an systematic underestimation of the depth of Sandy, not the lack of presence of the cyclone (using a different threshold of 32 m/s clearly increased the probabilities).

For longer lead times (3-8.5 days), ECMWF has the highest probabilites (except for the forecast issued 5.5 days before the event). The probabilities from the CMC model drops off quickly 3 days before the landfall, due to a large spread in the ensemble (not shown). The JMA forecast shows probabilities somewhat lower than NCEP and UK MetOffice but higher than CMC. Note that there is only one ensemble forecast evaluated per day from JMA. For NCEP, we see a “jumpy” behaviour for the medium range. This made the forecast difficult to interpret when there were large shifts in the probabilities between initial times.

The probability (around 20%) for the ECMWF ENS forecast 8.5 days prior to landfall indicated to forecasters that they could have some degree of confidence in the HRES forecast. The increase in probability 6.5 days prior to landfall to above 40 % further enhanced this confidence. It is this aspect of ECMWF’s forecasts for Sandy that distinguish the ECMWF forecasts from those of other centres.

4 Impact of sea-surface temperature

During the lifetime of hurricane Sandy the SST along the U.S east coast was unusually warm [Figure 10b compared to Figure 10a]. In this section we investigate the impact of these SST anomalies on the forecast of hurricane Sandy.

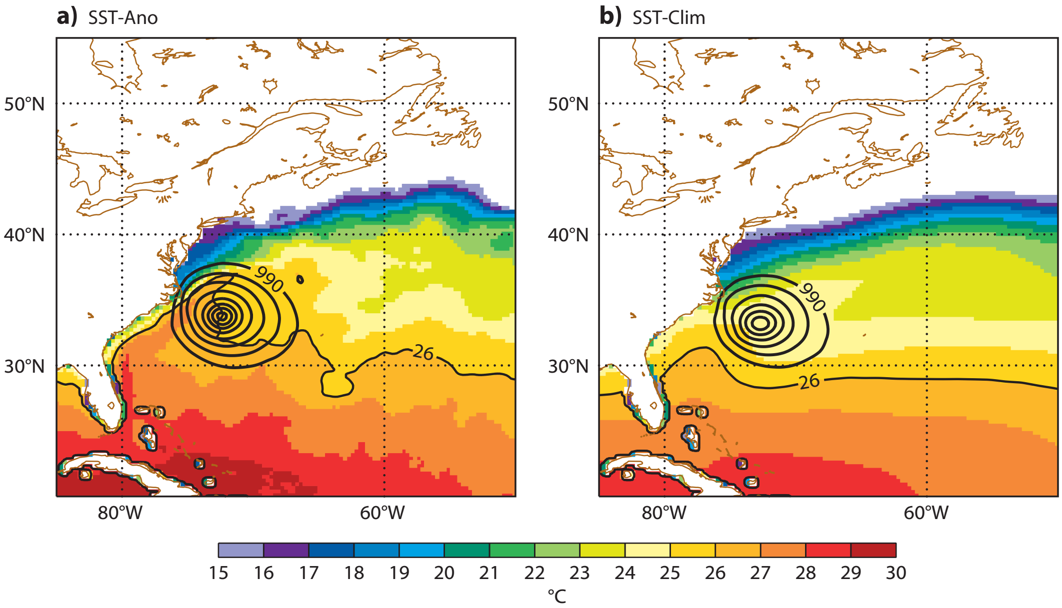

Figure 10: SST for 2012-10-24 00z +120h for different experiments together with the MSLP below 990 hPa to show the position of Sandy. The isotherm for 26 °C is highlighted.

In order to investigate the impact of the SST anomaly on the tropical cyclone two different ensemble experiments are run. The experiments are run with a spatial resolution of T_L639, 62 levels and 50 ensemble members. Forecasts are run from 2012-10-22 00z to 2012-10-26 00z every 24 hours. The operational setup of the ensemble prediction system uses persisted SST anomalies for the first 10 days of the forecasts. This experiment will be referred to as *SST-Ano* [Fig. 10a]. To test the sensitivity of the forecasts to the SST field a second experiment has the SST replaced by the SST climatology (experiment *SST-Clim*, Fig. 10b). Comparing the two figures we see that the tropical cyclone moved over water warmer than 26 °C until 1 day before landfall in *SST-Ano*, while the climatological SST is cooler (by a little more than 1 °C).

Figure 11 shows the strike probabilities and minimum pressure forecasts for ensemble experiments from the 24th 00z for *SST-Ano* (a) and *SST-Clim* (b). Regarding the tracks, the removal of the SST anomaly seems to improve the tracks for this particular initial time. However, the minimum pressure is deeper and better captured in the *SST-Ano*, which is expected due to the warmer SST and this leads to higher wind speeds.

In order to investigate the timing and depth difference for the cyclone in the two experiments, the position and the depth (indicated by the colour and size of the symbols) of the low-pressure system closest to the observed landfall position of Sandy are plotted in Figure 12. The different forecasts are initialised 2012-10-24 00z and the verification date is 2012-10-30 00z. It is apparent that the positions of the cyclones cover similar areas in the experiments. However, the ensemble of the cyclone's central pressure is shifted to lower values in experiment *SST-Ano*. For the forecasts issued on the 25th the *SST-Clim* ensemble seems to have a larger timing error that the *SST-Ano* ensemble - the cyclones are located further east, indicating a delayed landfall of Sandy.

Figure 13 shows the cyclone centre pressure error, averaged over all ensemble members, for the *SST-Ano* (red) and *SST-Clim* (blue). The forecasts are valid on 2012-11-29 12z, 12 hours before landfall. The evaluation time is selected to avoid the effect of some members having already made landfall and started to fill up and thereby reducing the minimum pressure. The results show a systematic difference between

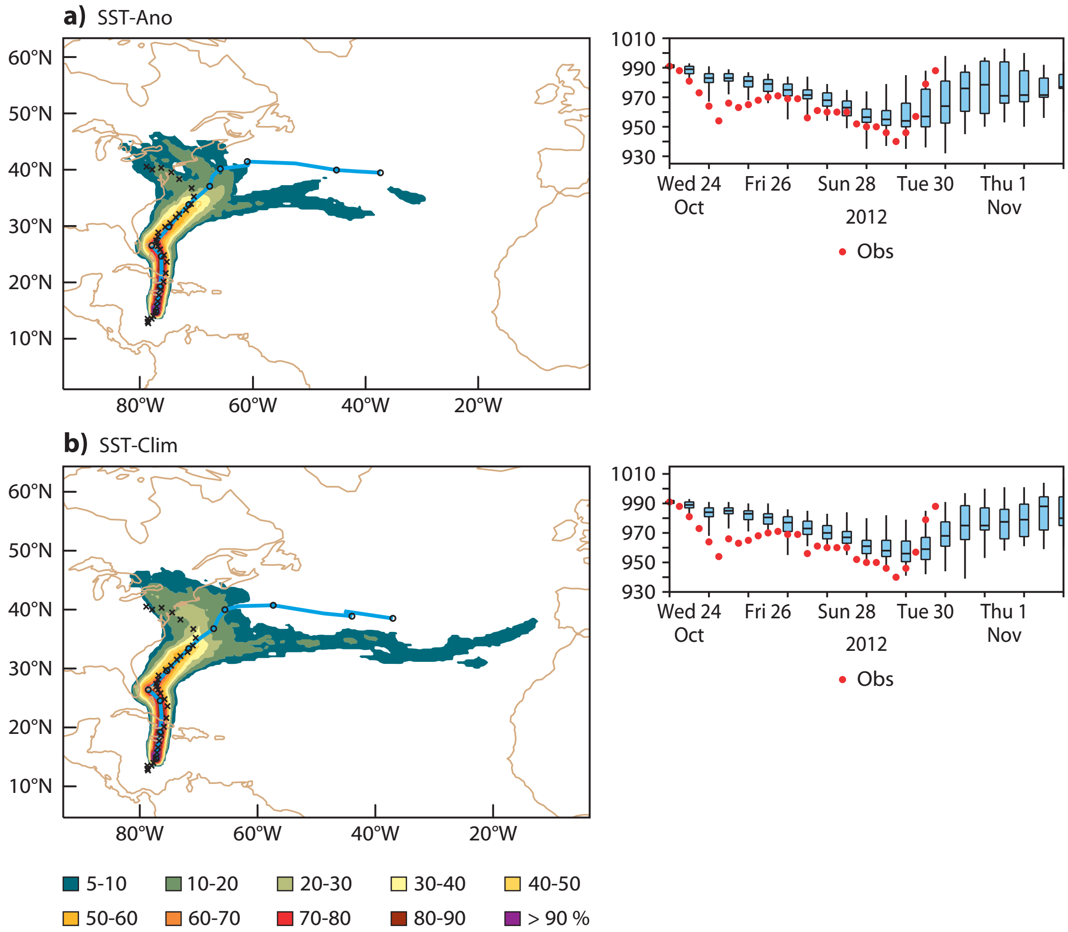

Figure 11: Strike probability map and minimum pressure for the SST-Ano (a) and SST-Clim (b) ENS forecasts. The mean position from the ensemble in plotted in (blue).

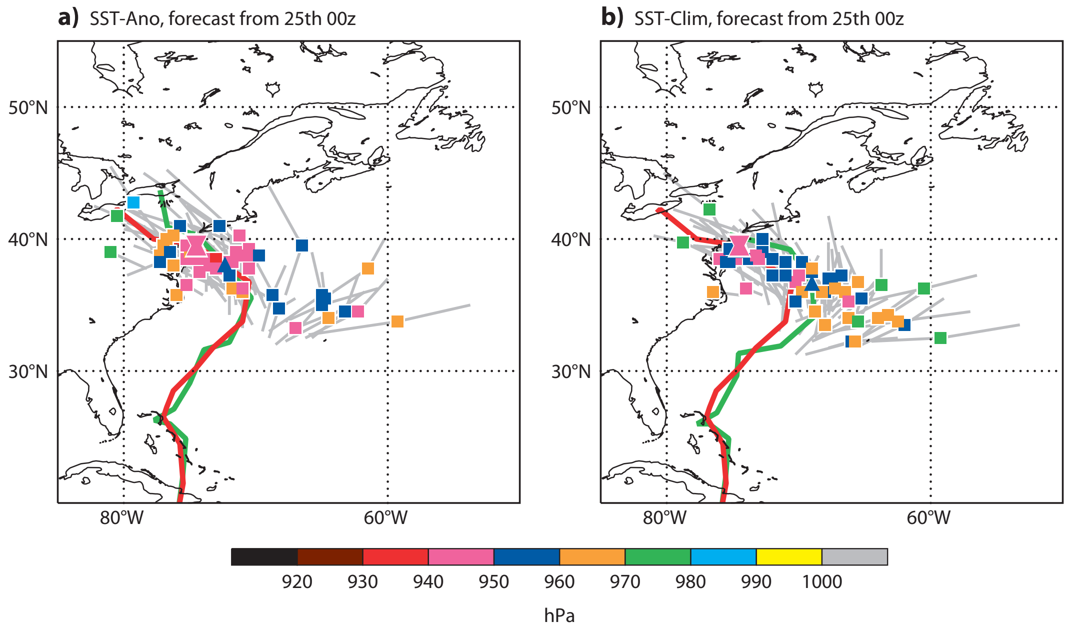

Figure 12: Same as Figure 6 but for experiment SST-Ano(left) and SST-Clim(right).

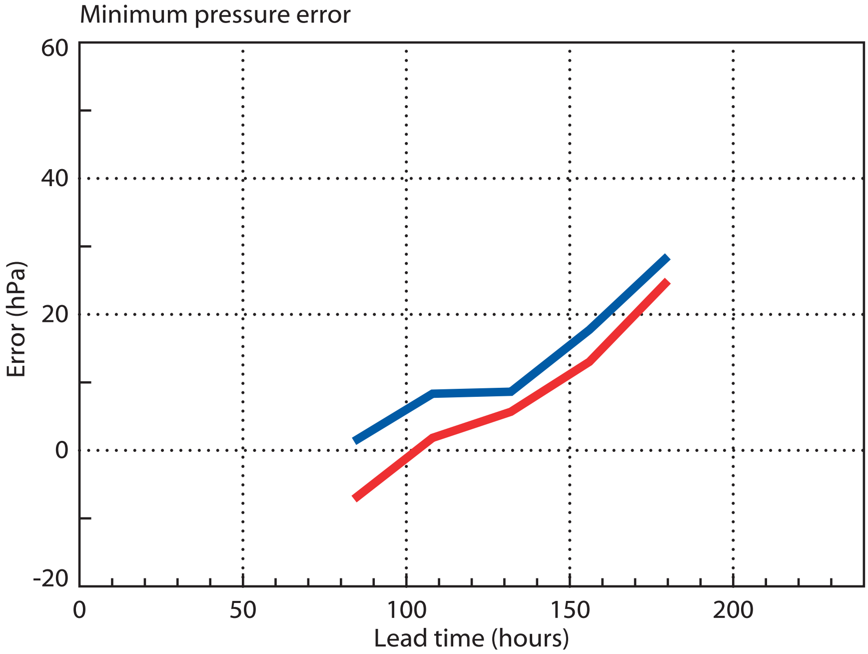

Figure 13: Error in depth of the cyclone centre. SST-Clim (blue), SST-Ano (red) and SST-Climbox (green).

the experiments. The *SST-Ano* has deeper cyclones for all initial times. This shows that the warm SST anomaly has an impact on the depth of the cyclones by between 5 and 10 hPa.

For three initial times, an ensemble using a coupled atmosphere-ocean model has been run. The SSTs are initialised from the ocean data-assimilation system used for the seasonal forecasts. The effect of an ocean-atmopsphere coupling on tropical cyclone behaviour was investigated in Takaya *et al.* (2010). In general, the coupling results in cooling the SSTs under a tropical cyclone, which dampens the heat-flux and weakens the storm. It was found that this inceased the systematic underestimation of the cyclone depth at that time (around 2009) in the ECMWF ensemble system. For the Sandy case, we did not found any degradation of the forecasts using the coupled model.

In this section we have investigated the impact of the warm SST anomaly along the east coast of the U.S on the evolution of hurricane Sandy. For predicting the landfall location on the New Jersey coast the SST anomaly does not seem to play an important role. For the depth of the cyclone the SST anomaly results in deeper more intense cyclones in the ensemble forecasts for all initial dates we considered in this study.

5 Impact of model resolution

In this section we investigate the impact of the horizontal resolution on the forecast of Sandy. We compare the T_L1279 HRES forecast (which corresponds to a grid resolution of 16 km) and the T_L639 control forecast from ENS (32 km), together with a forecast using T_L319 (64 km) and T_L159 (150 km) resolution. We have also produced 2 forecasts (from the 25th and 27th 00z) with a very high resolution for a global model (T_L3999, which corresponds to a grid resolution of 5 km). This model resolution is using a non-hydrostatic core but still parametrised deep convection. The experimentation with future resolutions is further described in Wedi *et al.* (2012). Note that all different resolutions were initialised from the same, T_L1279 (16 km), analysis.

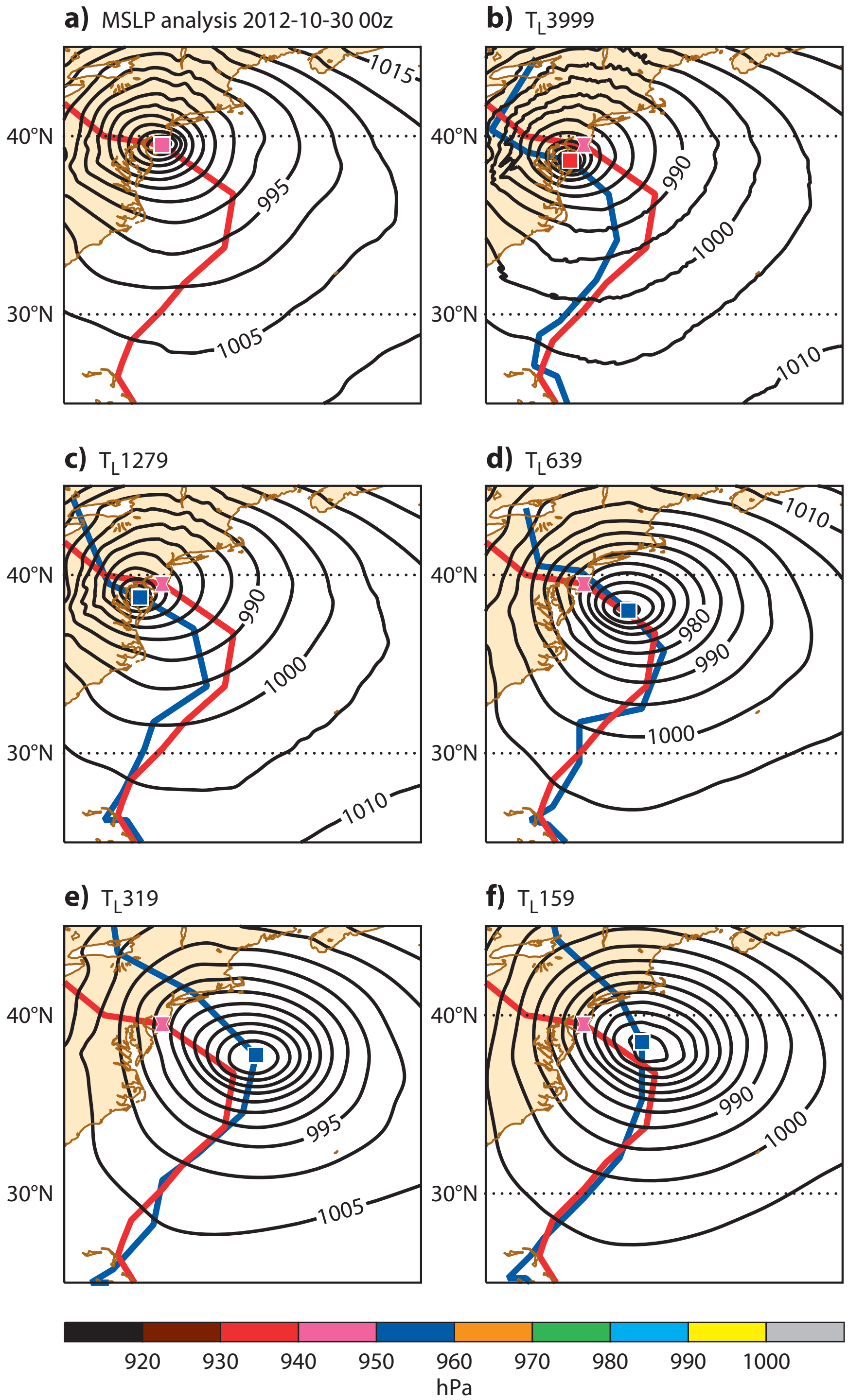

Figure 14: MSLP forecasts from 2012-10-25 00z valid 2012-10-30 00z (5 day forecasts) from different resolutions including the cyclone track (analys - red, forecasted -blue).

Figure 14 shows the MSLP from the the analysis at 2012-10-30 00z (a) and forecasts from 5 different model resolutions, issued 5 days earlier (25th 00z). In the plots, the cyclone tracks for the analysis (red) and forecasts (blue) are included. For the highest resolution (T_L3999, a), we find the deepest cyclone, deeper than the analysis (by around 5 hPa). It should be noted that the analysis is performed at T_L1279 resolution and so it not possible to assess the accuracy of the T_L3999 minimum surface pressure. The T_L1279 forecast has a position similar to the T_L3999 and the analysis. For the lower resolutions, the cyclone is still east of the coast, indicating a slower movement in the these forecasts. For the T_L319 and T_L159, the curve of the cyclone track to the west is not as sharp as in the analysis, while the two highest resolutions turn westward somewhat too early.

Figure 15 shows the same as Figure 14 but for 3-day forecasts initialised on 2012-10-27 00z. Here, we find an almost perfect forecast for T_L3999, while T_L1279 has the cyclone centre somewhat too far east. For all other resolutions, the centre is even further east and on a more northerly track, similar to the 5-day forecasts above. Furthermore, the central pressure minimum is higher with lower resolution.

Figure 16 shows the same as Figure 5a but for an ensemble using T_L159 resolution. The cyclone track is relatively well captured by the low resolution ensemble but the minimum pressure of the median ensemble member is too high by around 15 hPa for the U.S landfall. Figure 17 shows the same as Figure 8 but for the operational ENS (T_L639) and the T_L159 ENS. For long lead times the lower resolution gives higher probabilities of 850 hPa wind speeds greater than 38 m/s in vicinity of New York, than the operational resolution. The higher probabilities could be an artifact of the lack of ensemble spread in the low resolution ensemble. For this case (when the control forecast produced a good and consistent forecast), having a low spread will improve the ensemble forecast but averaged over many cases the forecasts are likely to be more unreliable (over-confident). For shorter lead times, the probabilities are somewhat under-predicted, which could be because the minimum pressure is not well captured with the low resolution.

Figure 18 shows forecasts for MSLP and significant wave height, initialised 2012-10-27 00z + 72h (same forecasts as in Figure 15). In the figures two buoys are marked. The time-series of the observations (hourly) for the buoys together with the forecasts for 2012-10-27 00z (3-hourly output) are plotted in Figure 19. The verified variables are MSLP (upper panels), wind speed (mid panels) and significant wave height (lower panels). The western buoy (hourglass symbol) is located close to New York harbour and the second buoy (diamond symbol) somewhat further east. The centre of the hurricane passed south of the two buoys.

The results for the MSLP shows the differences in timing of the hurricane as seen above; with decreased resolution the hurricane passes later. The timing for T_L3999 is almost perfect, while the minimum pressure is not deep enough. This is partly, but probably not completely, because we have used 3-hourly model output and the observations are hourly. For the T_L639 and T_L319 resolutions, the minimum pressure is better captured, but it could be an artifact of an error in the cyclone track (too northerly track as seen in Figure 15). For T_L319, the wind speed was temporarily lower when the pressure minimum passed, which is a sign of the closeness to the eye of the storm.

For the wind speed we also see the difference in timing. The maximum of the wind speed is well captured for all resolutions for the eastern buoy (somewhat underestimated by T_L319). For the western buoy, which is located closer to New York harbour, the maximum wind speed is clearly underestimated by T_L319, probably because the resolution of the coast-line. For the wave height forecasts, we see that T_L3999 produced an almost perfect forecast of the peak for the western buoy, while the wave height was underestimated by all other resolutions. It shows that the higher resolution for the wave model allowed high waves close to the coast. This difference is also appearent in the forecast maps of the wave height

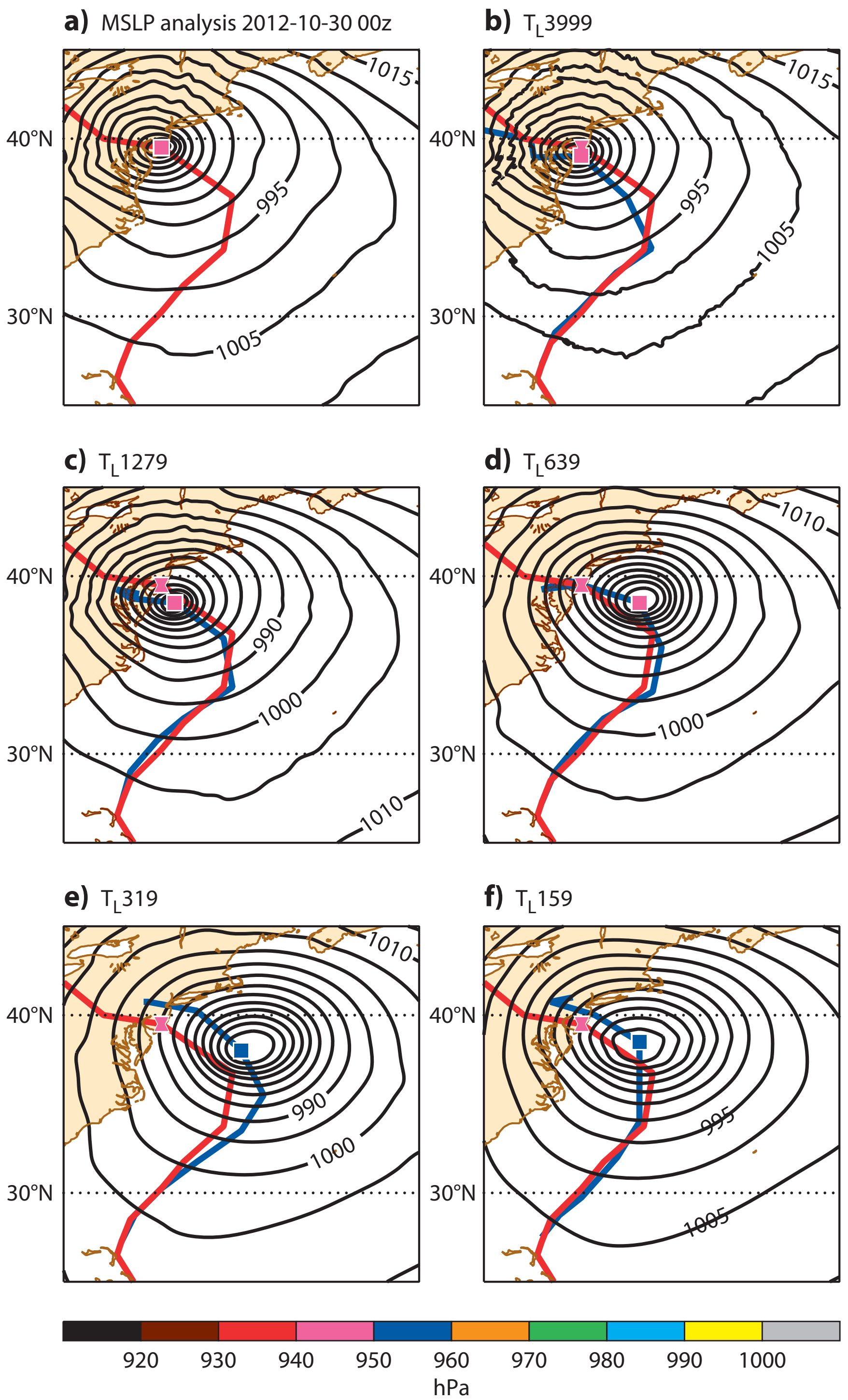

Figure 15: MSLP forecasts from 2012-10-27 00z valid 2012-10-30 00z (3 day forecasts) from different resolutions including the cyclone track (analys - red, forecasted -blue).

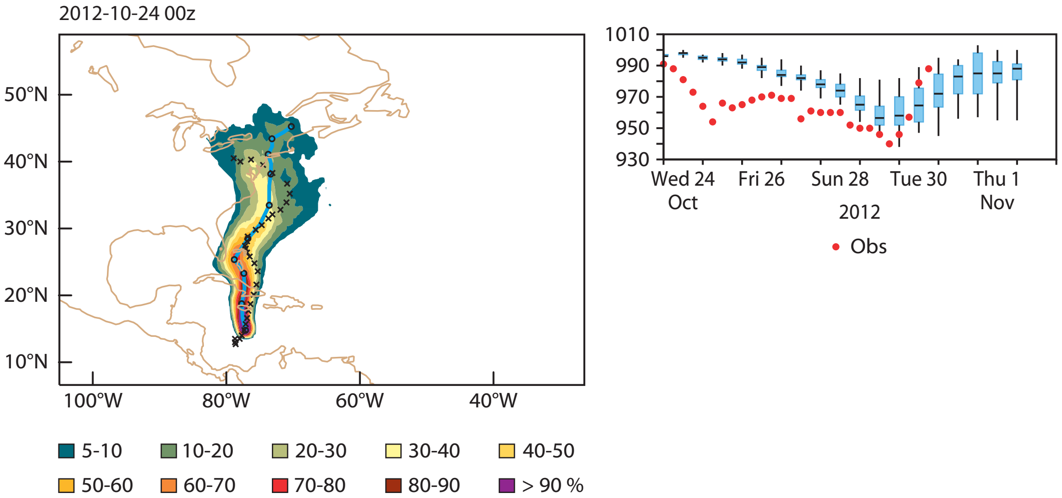

Figure 16: Strike probability map and minimum pressure for the T_L159 ENS forecast. The mean position from the ensemble in plotted in (blue).

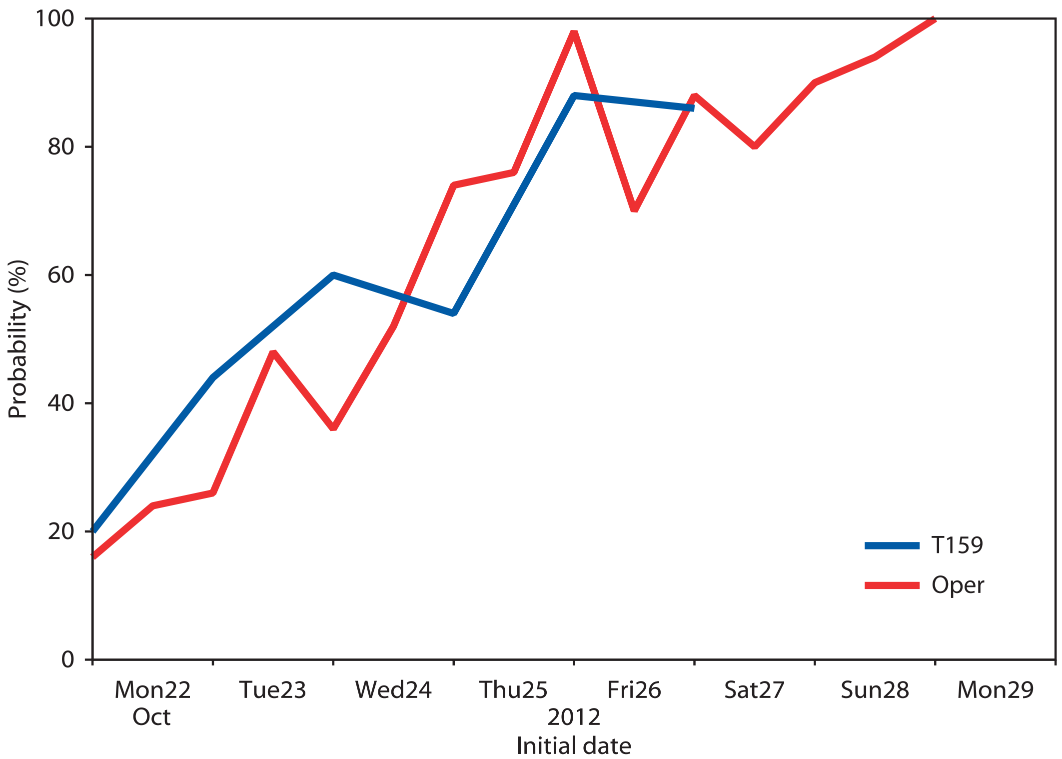

Figure 17: Probability of 850 hPa wind speed greater than 38 m/s inside a radius of 100 km for New York Harbour between 2012-10-29 12z and 2012-10-30 12z. Operational ENS (T_L639,red) and T_L159 ENS (blue).

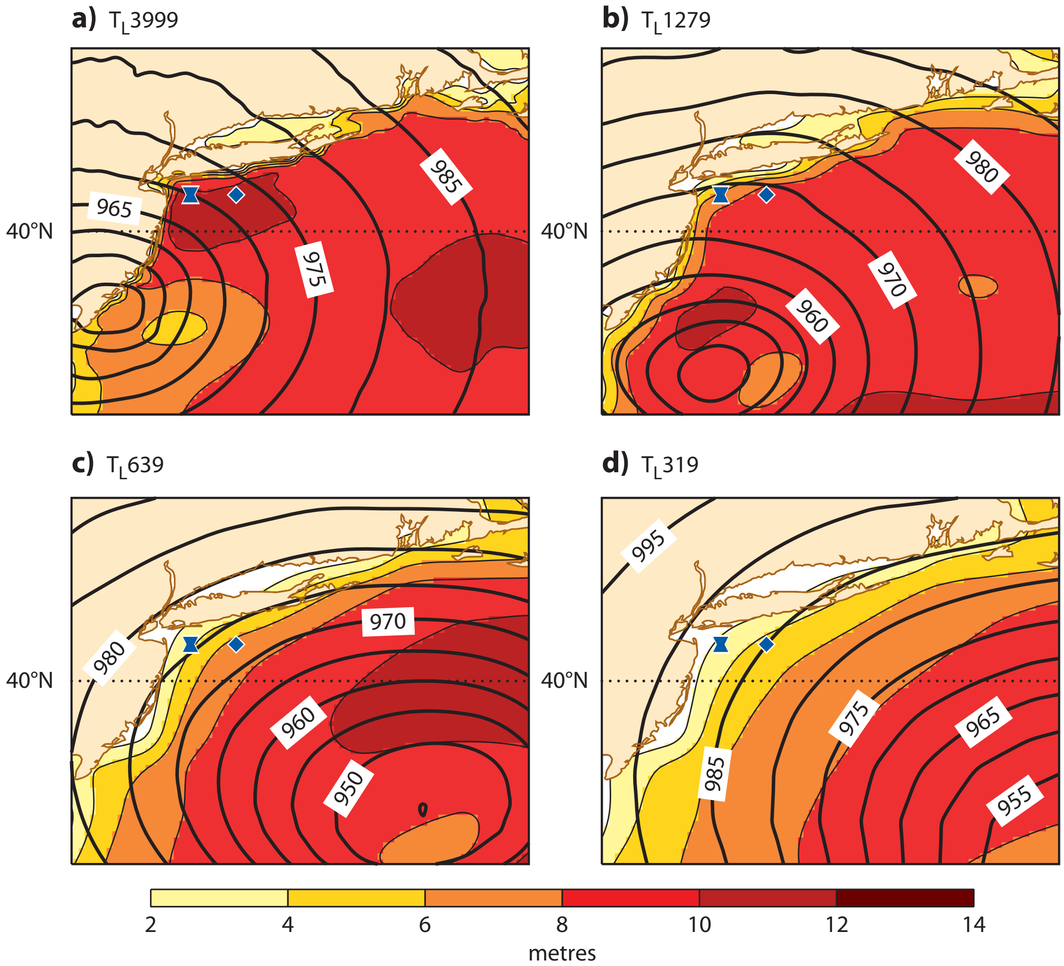

Figure 18: MSLP and significant wave height from 2012-10-27 00z +72h for different resolutions. (The legend and the size of the buoy symbols have to be fixed.)

(Figure 18). For the eastern buoy the results are more similar regarding the peak of the wave height, although T_L3999 captures the peak best.

Figure 20 shows the +24h accumulated precipitation between 2012-10-30 00z to 2012-10-31 00z from forecasts initialised 2012-10-27 00z and the U.S radar network NEXRAD (a). In the figures, also the MSLP valid at 2012-10-30 12z is plotted. From the results in Figure 15 we know that a timing difference is present between the experiments. The timing difference leads to different precipitation patterns; while the cyclones in T_L3999 and T_L1279 have hit land the other resolutions have the main part of the cyclone over sea, which also effects the precipitation pattern. For the highest resolution we see a good agreement with the radar, due to a well resolved orography and a good timing of the cyclone.

In this section, we have investigated the impact of the model resolution on the Sandy forecasts. For capturing the cyclone track, the resolution does not seem to play a crucial role; the T_L159 ensemble has a similar performance as the T_L639 for the cyclone track. However, we see an indication of a slower propagation speed in the lower resolution runs and the amplitude of the minimum pressure is not as well captured. With higher resolutions, the extremes in wind and precipitation are better captured.

6 Impact of different components of the observing system

In the data assimilation system, observations from different kind of platforms are used to obtain the best possible estimate of the initial conditions. To investigate the role of the different platforms, a number of data assimilation experiments have been undertaken where different kinds of satellite observations were withheld. From the new analyses, forecasts for Sandy case were run. The results are summarised in McNally *et al.* (2013), where the largest impact was obtained by withholding observations from polar orbiting satellites.

In order to explore the impact of witholding polar orbiting satellite observations in a probabilistic framework, the ensemble of data-assimilations (EDA) was re-run and the results were used both as input to the HRES analysis and for the initial ensemble perturbations (hereafter referred to as NoPol). The data-assimilation experiment started on 2012-10-09 and the first ENS forecast was initialised 2012-10-21 00z. The result are compared to the operational ENS. In this comparison, the NoPol experiment has an advantage of using a longer data assimilation window (12-hour, delayed cut-off) than the operational ENS (which is using 6-hour window for the last cycle, short cut-off). This is an advantage for the NoPol experiment.

Figure 21 shows the cyclone positions in forecasts initialised 2012-10-26 00z for the operational ENS forecast and the NoPol ENS. For this initial time, there is a clear difference in the cyclone positions; the NoPol ensemble has less members curving towards the New Jersey coast and more members on the northerly track. There are also a few members with an eastward track resulting in no landfall. Overall, the dispersion in the cyclone positions in the NoPol ensemble is larger than in the operational ensemble. Not withstanding these differences in the ensemble forecasts, we see that the control forecast from the NoPol experiment produced a relatively good forecast of the landfall.

To study all forecasts from the NoPol experiment, Figure 22 shows the probabilities for 850 hPa wind speed greater than 38 m/s inside a radius of 100 km for New York Harbour between 2012-10-29 12z and 2012-10-30 12z for the NoPol experiment (blue) and the operational ENS (red). The results show that for most of the forecasts the probabilities for a landfalling hurricane were decreased by not including the polar orbiting satellite data, but even so a fraction of the ensemble members still predicted a landfall.

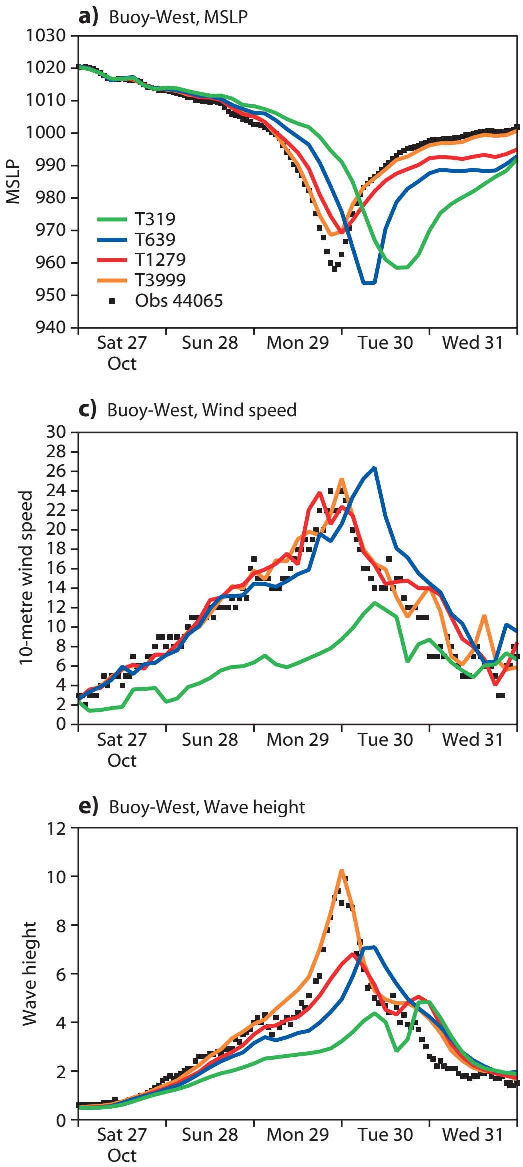

Figure 19: Observations for two buoys east of New York harbour and forecast data from 2012-10-27 00z.

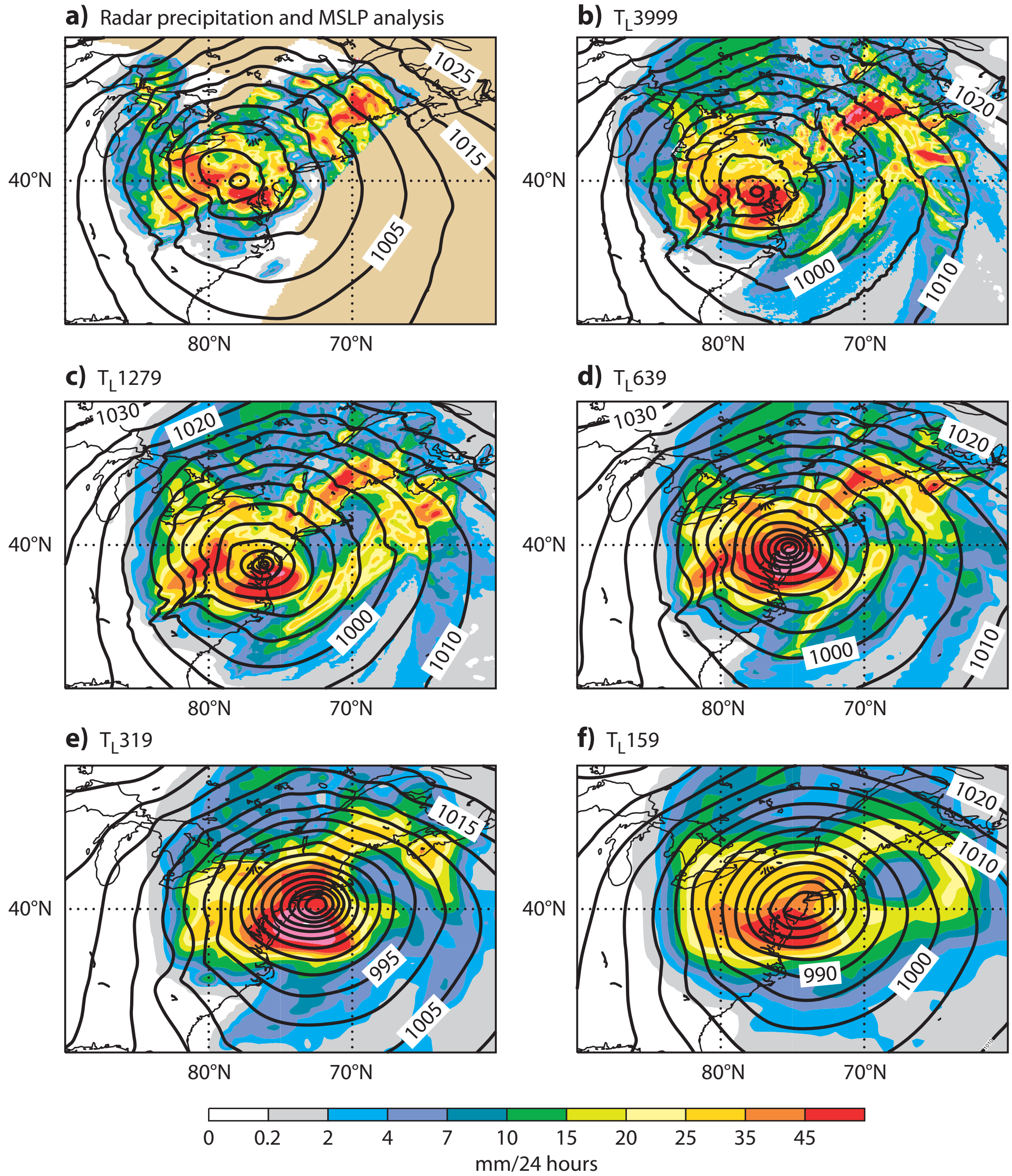

Figure 20: Precipitation forecasts from 2012-10-27 00z valid between 2012-10-30 00z to 2012-10-31 00z, MSLP for 2012-10-30 12z.

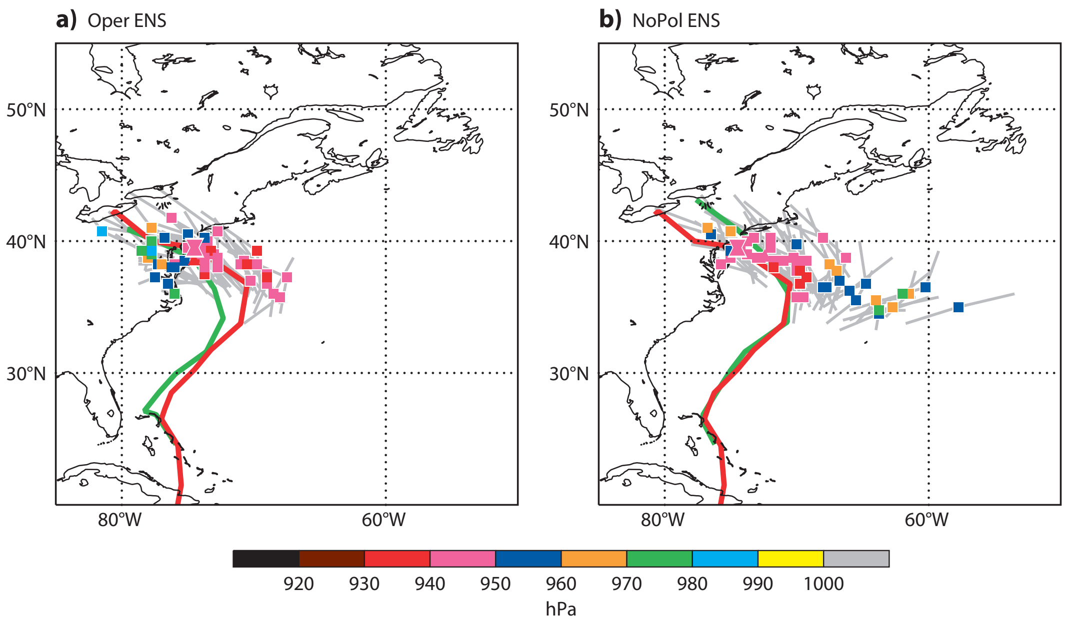

Figure 21: Ensemble forecasts from 2012-10-26 00z. Position of the cyclone centre closest for the landfall position in ensemble forecast (squares) including the trajectory for -12 hours to +12 hours (grey lines). Cyclone track from control forecast (blue) and position at 2012-10-30 00z (triangle symbol). Landfall position in hourglass symbol and the observed cyclone track (red).

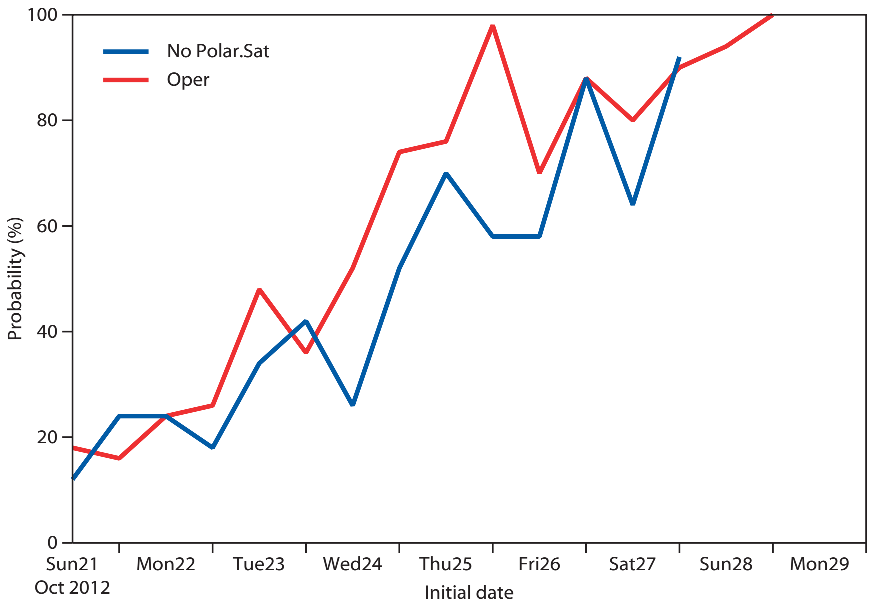

Figure 22: Probability of 850 hPa wind speed greater than 38 m/s inside a radius of 100 km for New York Harbour between 2012-10-29 12z and 2012-10-30 12z.

7 Discussion

In this report, we have discussed the predictability for the landfall of hurricane Sandy, affecting the New York City area on October 30th 2012. The cyclone made an unusual turn toward the west before making landfall. The westward movement and rapid deepening from the 29th was most likely due to an interaction with a trough over the U.S. Therefore both the prediction of the tropical cyclone and the U.S trough were of importance. The results show that ECMWF operational forecasts 8 days before landfall gave a strong and accurate indication of what was to happen. From 7 days before the landfall the high-resolution forecasts were consistent in its prediction of the landfall. The results from the ensemble forecasts allowed a significant degree of confidence to be attached to these forecasts but also showed signs of a too slow movement of the cyclone, which led to a timing error of the landfall.

The TIGGE archive has been used to compare predictions from different forecasting centres. The results shows that the ensembles from NCEP and UKMO started to pick up the risk for a deep cyclone making landfall 7 days (+168h) before the landfall and the ECMWF ensemble one day earlier (+8 days). Comparing the performance between the centres, ECMWF had the highest probability for the cyclone landfall for most initial forecast times in the medium range. We also found that UKMO seemed to under-predict the depth of the cyclone compared ECMWF and NCEP and that the CMC ensemble had a large spread among the members. To evaluate whether the ensemble spread is reliable, the ensemble spread of tropical cyclone tracks needs to be evaluated over many cases. Comparisons between different forecasting centres for tropical cyclones can be found in e.g. Hamill *et al.* (2011); Yamaguchi *et al.* (2012).

We have investigated the impact of the warm SST anomaly present east of the U.S west-coast at the time of the hurricane by running an ensemble with climatological SST. We found that the anomaly was not critical for forecasting the position of the landfall but for the depth of the cyclone.

We have also compared forecasts from 5 different model resolutions, spanning from 5 km (T_L3999) to 150 km (T_L159). We found that the resolution was not the major factor for determining the cyclone track, but the model resolution had, as expected, a large influence on the strength of the cyclone. Our results also show a difference between the resolutions in terms of propagation speed of the cyclone. The results are in line with what was found for extra-tropical storms in ensemble forecasts in Froude *et al.* (2007). This is a result that warrants further investigation over many cases. For the two initial dates investigated more in depth, there is also a difference in the sharpness of the westward turn. Moreover, wind speed, significant wave height and precipitation were compared for the different resolutions. With the highest resolution, also the extreme wave heights close to the coast were captured. Regarding the precipitation, the high resolution runs had a larger influence from orographic features, which were not captured in the low resolution runs. The largest impact in New York City was due to the storm surge connected to Sandy. Because the ECMWF forecasting system does not include a storm surge model, this aspect has not been investigated.

Finally, we have investigated the impact on different observation systems for the forecast. McNally *et al.* (2013) found that a large impact was obtained by removing the polar orbiting satellites. We extended the experimentation to ensemble forecasts with similar results, although a predictive signal for Sandy is still present in the forecasts even with these satellite observations removed.

The early forecasts of Sandy also triggered a set of additional ”targeted” observations to be made to enhance the observational coverage relevant for the prediction of the developing storm; these were used in real-time to improve the predictive skill of the various forecasts. Between 2012-10-26 and 2012-10-29, 30 to 40 additional drop-sondes and radiosondes were assimilated for 00z and 12z. Further investigation is need to determine the impact of these observations.

In this report we have focused on a single severe weather event and we have discussed several sensitivities of the forecasting system. Experimentation for large samples of cases would be required to confirm the general validity of the sensitivities identified here.

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