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The impact of climate change on the critical weather conditions at Schiphol airport (**Impact**)

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The impact of climate change on the critical weather conditions at Schiphol airport (Impact)

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Content

Samenvatting

Schiphol Mainport (zie figuur 1.1) en zijn netwerk van internationale verbindingen zijn van essentieel belang voor de economische positie van Nederland in Europa. Vanwege haar ligging vlakbij de zee en 4 - 6 m onder de zeespiegel in de Haarlemmermeer, zijn de luchthaven en haar omgeving kwetsbaar voor veranderingen in ons klimaat. De luchthaven operatie is daarnaast erg gevoelig voor kritieke weersomstandigheden zoals mist, intensieve neerslag en hevige wind. Deze omstandigheden leiden tot een verlies in de beschikbare luchthavencapaciteit (zie tabel 2.1) en indien niet op tijd voorspelt tot extra vertragingen in het luchtruim. Bovendien heeft dit slechte weer een grote impact op de luchtvaartveiligheid (zie figuur 1.2). Een duurzame en veilige operatie van de luchthaven, nu en in de toekomst, vereist betrouwbare weersinformatie op lokale schaal. Als gevolg van klimaatverandering verwachten we dat ook de variabiliteit van het weer op de luchthaven en de frequentie en intensiteit van kritieke weersomstandigheden zullen veranderen, maar een precieze kwantificering daarvan ontbreekt. Onze huidige weer- en klimaatmodellen zijn niet goed in staat om deze veranderingen met voldoende nauwkeurigheid te bepalen. De belangrijkste doelstelling van dit project is daarom het verstrekken en demonstreren van het volgende generatie weer- en klimaatmodel HARMONIE. Dit is een nieuw model dat beter geschikt lijkt om het effect van klimaatverandering op lokale kritieke weersomstandigheden op de luchthaven te kwantificeren en te begrijpen. Bovendien zal kennis uit dit project worden gebruikt om de kwaliteit van onze huidige en toekomstige weersvoorspellingen te verbeteren.

Het HARMONIE model dat in dit project wordt gebruikt, is ontwikkeld door de meteorologische instituten van 27 Europese en Noord-Afrikaanse landen (de *"HIRLAM-ALADIN samenwerking"*, zie figuur 3.1). HARMONIE is een niet-hydrostatisch roosterpuntsmodel dat kan worden toegepast op ruimtelijke resoluties van 1 - 2 km, of zelfs minder. Niet-hydrostatisch betekent dat verticale atmosferische bewegingen expliciet worden opgelost door de modelvergelijkingen. Als gevolg daarvan kan het model worden toegepast voor bepaalde typen gevaarlijk weer, zoals zwaar onweer met sterke verticale windsnelheden (zogenaamde convectie gebeurtenissen) en sterke windsnelheden in de buurt van obstakels en bergen. Voor dit soort zwaar weer is de bruikbaarheid van onze huidige hydrostatische modellen, zoals het weermodel HIRLAM en het klimaatmodel RACMO, vaak beperkt. Naast extreme weersomstandigheden, is HARMONIE ook beter geschikt voor het verwachten van andere soorten weersomstandigheden, zoals de vorming van lage bewolking (zie figuur 3.2), mist en verschillende vormen van neerslag (aanvriezende regen, sneeuw en te zijner tijd hagel).

In dit project wordt het potentieel van het HARMONIE model, om meer gedetailleerdere en nauwkeurigere weersvoorspellingen voor luchthaven Schiphol te leveren dan ons huidige operationele weermodel HIRLAM, nagegaan in het huidige klimaat. Voor dit onderzoek zijn HARMONIE modelgegevens gesimuleerd voor een selectie van weer casestudies (zie tabel 4.1). De geselecteerde cases vertegenwoordigen voornamelijk de weerparameters wind, zicht, lage wolken en neerslag. Deze weerparameters, en plotselinge veranderingen daar-

in, zijn geïdentificeerd als zijnde het meest kritiek voor de operatie op Schiphol (zie Schiphol Inventarisatie, Hoofdstuk 2). De operationele besluitvorming van de belangrijkste stakeholders op de luchthaven, de Schiphol Groep (AAS), de Luchtverkeersleiding Nederland (LVNL) en de luchtvaartmaatschappij KLM, is sterk afhankelijk van deze weerparameters. Om te kunnen anticiperen op toekomstig weer, hebben we voor een deel van de weer cases tevens onderzocht hoe deze zich ontwikkelen bij veranderingen in de oppervlaktetemperatuur van het zeewater, welke een van de belangrijkste klimatologische factoren is die onderhevig is aan veranderingen in een toekomstig klimaat. De belangrijkste resultaten van de weer casestudies met betrekking tot de weerparameters die essentieel zijn voor de operatie op Schiphol zijn:

Hevige wind

Het niet-hydrostatische model HARMONIE lost, in tegenstelling tot HIRLAM, expliciet verticale convectieve bewegingen op. Als gevolg daarvan worden extreme wind situaties, zoals downbursts (bijv. op 14 juli 2010: windsnelheden tot 100 km/uur, windstoten tot 140 km/uur), door het model realistischer opgepakt dan door HiRLAM. Ook de hogere ruimtelijke resolutie van HARMONIE (1 – 2 km versus 10 km in HiRLAM) resulteert in een meer gedetailleerd beeld van de wind. In het algemeen kan HARMONIE kleine gebieden representeren met zeer hoge windsnelheden, die meestal afwezig zijn in HiRLAM (zie figuur 4.6). Ten slotte, als we het huidige operationele model HiRLAM vergelijken met HARMONIE, dan zien we ook dat in gevallen waarin HiRLAM goed presteert, zoals stormen op grote synoptische schaal (orde 1000 km), HARMONIE vergelijkbare resultaten geeft, maar op een hogere resolutie en met meer detail.

Mist

Ten opzichte van HIRLAM, lijkt HARMONIE beter in staat om de dynamische structuur van mist velden en van extremen in wolkenwater op de laagste modelniveaus te voorspellen. Desondanks hebben casestudies van stralingsmist situaties laten zien dat HARMONIE, net zoals andere modellen, moeilijkheden heeft bij het voorspellen van de exacte begintijd en de ontwikkeling van de mist. Een hoge verticale resolutie in de laagste honderd meters van het model lijkt daarbij van groot belang. Een lagere verticale resolutie leidt in het algemeen tot een vertraging in het ontstaan van mist. We moeten echter voorzichtig zijn met deze conclusie omdat het aantal gevallen dat we hebben bestudeerd klein is en in sommige gevallen we hebben waargenomen dat niet alle belangrijke modelparameters verbeteren bij een verhoging van de verticale resolutie van het model.

Lage wolken

Ondanks dat in het algemeen ook lage wolken beter worden opgepakt door HARMONIE, worden stratocumulus wolken vaak onderschat door het model (zie figuur 4.15) vanwege hun relatieve ondiepte (ze zijn maar een paar honderd meter dik). De grove verticale resolutie van het model maakt dat deze wolken slechts op 1 of 2 modellagen in het model aanwezig zijn. Hierdoor is de representatie veel gevoeliger voor kleine fouten. Zo kan een fout in de orde van 0,1 °C in temperatuur al het verschil maken tussen een heldere atmosfeer of een die is gevuld met lage wolken. Daarom zal net als bij het voorspellen van mist, ook de voorspelling van de vorming van lage wolken waarschijnlijk profiteren van een fijnere verticale resolutie van het model.

Om deze hypothese te verifiëren, werd een vergelijkbaar experiment uitgevoerd met een zeer hoge resolutie (orde 10 m) 'Large Eddy Simulation' (LES) model. Daarbij werd aangetoond dat een dergelijk model goed in staat is om de stratocumulus wolkenlaag te voorspellen (zie figuur 4.16). Door hun fijne resolutie zijn deze LES modellen echter te rekenintensief voor operationeel gebruik.

Intensieve neerslag

Verschillende casestudies hebben laten zien dat HARMONIE zware neerslag en de algemene vorm van neerslagpatronen goed voorspelt. Regenintensiteit en het tijdstip van neerslag, lijkt echter zeer gevoelig voor de grootte van het rekendomein van het model (zie figuur 4.9). Voor kleinere rekendomeinen begint de neerslag vaak te vroeg en is de intensiteit te laag. Om het hoge resolutie model HARMONIE met vertrouwen te kunnen toepassen, waarbij betrouwbare resultaten worden geproduceerd en waarbij tegelijkertijd de benodigde rekentijd binnen aanvaardbare grenzen ligt, wordt een domeingrootte van 400x400 roosterpunten, met de standaard horizontale resolutie van 2.5x2.5 km, aanbevolen. Dit is nodig om de ontwikkeling van convectieve structuren door het model, zoals stormen en buienlijnen, te kunnen garanderen. Deze domeingrootte zorgt ervoor dat HARMONIE niet alleen kleinere schaal informatie aan HiRLAM toevoegt, maar dat de voordelen van een niet-hydrostatisch model voor het maken van een state-of-the-art voorspelling ook echt tot zijn recht komen.

De impact van de klimaatverandering

Voor een aantal casestudies is HARMONIE toegepast om het effect van een verhoogde oppervlaktetemperatuur van het zeewater op neerslaghoeveelheden en wind te bestuderen. Het bleek dat dit effect het meest eenvoudig te zien was voor weersystemen die naderen vanuit het westen, dat wil zeggen over zee, en die voldoende tijd hebben om hun invloed uit te oefenen. Het belangrijkste effect van deze weersystemen lijkt te zijn dat convectie in de buurt van de kust makkelijker wordt aangezet, dat neerslagpatronen veranderen en dat regenhoeveelheden en wind in het kustgebied intenser zijn.

HARMONIE is ook toegepast om het stedelijk hitte-eiland effect van Rotterdam te bestuderen. Een stedelijk hitte-eiland is een grootstedelijk gebied dat aanzienlijk warmer is dan het omringende platteland. HARMONIE is in staat om dit effect te modelleren met behulp van een stads energie budget module waar het model over beschikt. Die module berekent het effect van de bebouwde omgeving en de heterogeniteit van het landschap op de lokale weersomstandigheden, zoals bijv. de 2m temperatuur. Gebleken is dat de uitkomsten van hoge resolutie modellen zoals HARMONIE zeer gevoelig zijn voor de landgebruik classificatie gegevens die door het model worden gebruikt (zie figuur 4.18). Dit zal ook van belang zijn voor het modelleren van andere lokale weersverschijnselen die beïnvloed worden door de heterogeniteit van het oppervlak, zoals bijv. convectieve neerslag.

We hebben ook onderzocht wat de skill van HARMONIE is om maandelijkse neerslaghoeveelheden te voorspellen in de zomer. Voor dat doel werd de periode augustus 2006 geëvalueerd. In deze periode werd een record hoeveelheid neerslag waargenomen, vooral bij de kust waar de hoeveelheden meer dan 300% van het klimatologische gemiddelde bedroegen (zie figuur 5.3). Voor dit onderzoek is HARMONIE toegepast in twee verschillende modi: a) Hindcast modus waarin opeenvolgende dagelijkse weervoorspellingen worden gemaakt die elke dag starten vanaf de ECMWF analyse, en b) Klimaat modus waarin het model slechts een keer wordt geïnitialiseerd op 31 juli en dan continu draait tot het einde van augustus. Beide modellen gebruiken dezelfde randvoorwaarden, in dit geval de ECMWF analyse. De hindcast resultaten zijn indicatief voor wat we kunnen verwachten van HARMONIE bij gebruik als een operationele weersvoorspelling model. De klimaatruns zijn een indicatie van hoe HARMONIE zou presteren als een regionaal klimaatmodel, in dit geval gevoed met perfecte randvoorwaarden.

De resultaten tonen aan dat zowel de klimaat als de hindcast simulaties de maandelijkse neerslag overschatten met ongeveer 15% (zie tabel 5.1). Beide simulaties voorspellen het kwalitatieve beeld van meer neerslag in de kustgebieden dan in het binnenland, in overeenstemming met de waarnemingen. Echter, neerslag in het binnenland wordt overschat en de piekwaarde van de hindcast run in de buurt van de kust is veel te hoog (zie figuur 5.6). Verder onderzoek heeft aangetoond dat de meest waarschijnlijke oorzaak van de hogere hoeveelheid neerslag in HARMONIE een veel te hoge oppervlakte verdamping is (zie figuur 5.7), veroorzaakt door te hoge bodemvocht waarden in het model.

Het wordt aangenomen dat de hogere hoeveelheid neerslag, zoals waargenomen in augustus 2006, wordt veroorzaakt door een hogere oppervlaktetemperatuur van het zeewater (SST). Om de rol van de SST op de toename van neerslag te onderzoeken, zijn twee extra klimaat runs gemaakt met een verhoogde (+2 °C) en een verlaagde (-2 °C) SST. Het blijkt dat het veranderen van de SST een sterke invloed heeft op de maandelijkse neerslagsom en dat de meest significante verschillen optreden in het kustgebied (zie tabel 5.2 en de figuren 5.8 en 5.9). Hogere SST's geven een grotere hoeveelheid neerslag in het kustgebied maar in het binnenland meer dan 100 km van de kust heeft de SST geen effect. Ook is gebleken dat de modellen profiteren van hoge resolutie SST velden gebaseerd op NOAA satellietwaarnemingen. Dit is aangetoond met RACMO hindcasts (zie figuur 5.11), omdat het voor Harmonie technisch nog niet mogelijk is om deze hoge resolutie SST's te gebruiken. In de operationele setup van HARMONIE wordt het gebruik van deze SST's sterk aanbevolen.

Ten slotte, een aantal nieuwe verificatiemethoden zijn onderzocht waarvan wij geloven dat ze beter geschikt zijn om de skill van hoge resolutie modellen zoals Harmonie te demonstreren, in het bijzonder voor neerslagverwachtingen. De nieuwe methoden proberen het ‘double penalty’ probleem te omzeilen waar conventionele verificatiemethoden last van hebben, bijvoorbeeld: een bui wordt voorspeld waar hij niet is waargenomen, waardoor een 'vals alarm' wordt gehesen, en de waargenomen bui is niet voorspeld, wat telt als een ‘misser’. De toepassing van deze methoden voor HARMONIE zal verder worden onderzocht in de 2de tranche van het KvK programma.

Summary

Schiphol Mainport (cf. figure 1.1) and its network of international connections are of vital importance for the economic position of the Netherlands in Europe. Due to its location near the sea and 4 – 6 m below sea level in the Haarlemmermeer, the airport and its surrounding area are vulnerable to changes in our climate. The airport operation is very sensitive to critical weather conditions such as fog, intense precipitation and heavy winds. These conditions lead to a loss in the available airport capacity (cf. table 2.1) and if not foreseen in time to additional airspace delays. Furthermore, adverse weather has a high impact on aviation safety (cf. figure 1.2). A sustainable and safe airport operation, now and in the future, requires reliable weather information on local scales. Due to climate change, we also expect that the variability of the airport weather and the frequency and intensity of critical weather events will change, but a precise quantification is lacking. Our present day weather and climate models are not well suited to determine these changes with sufficient accuracy. The main objective of this project therefore is to provide and demonstrate the next generation weather and climate model HARMONIE. This is a new model that seems better suited to quantify and understand the effect of climate change on local critical weather conditions at the airport. Furthermore, knowledge from this project will be used to improve the quality of our present and future weather forecasts.

The HARMONIE model used in this project has been developed by the meteorological institutes of 27 European and North African countries (the *"HiRLAM-ALADIN collaboration"*, cf. figure 3.1). HARMONIE is a non-hydrostatic grid-point model that can be applied at spatial resolutions of 1 – 2 km, or even less. Being non-hydrostatic means that vertical atmospheric motions are solved explicitly by the model equations. As a result, the model can be used for certain types of hazardous weather, such as heavy thunderstorms with strong vertical winds (so called convective events) and strong winds near obstacles and mountains. For these types of severe weather the usefulness of our present day hydrostatic models, such as the weather model HiRLAM and the climate model RACMO, is often limited. Besides extreme weather conditions, HARMONIE is also better suited to predict other types of weather events, such as the formation of low clouds (cf. figure 3.2), fog and various types of precipitation (freezing rain, snow and in due course hail).

In this project, the capability of the HARMONIE model to provide more detailed and more accurate weather predictions for Schiphol airport than our present day operational weather prediction model HIRLAM is assessed in the current climate. For this study HARMONIE model data is simulated for a selection of weather case studies (cf. table 4.1). The selected cases mainly represent the weather parameters wind, surface visibility, low clouds and precipitation. These weather parameters, and sudden changes therein, have been identified to be most critical for Schiphol operation (cf. Schiphol Inventory, chapter 2). Operational decision making of the main stakeholders at the airport, the Schiphol Group (AAS), the Air Traffic Control the Netherlands (NVNL) and KLM airlines, highly depends on these weather parameters. To be able to anticipate future

weather, for some of the weather cases we have also studied how they would evolve for changes in the sea surface temperature, which is one of the most important climatological factors that is subject to change in a future climate. The most important results of the weather case studies, in relation to the weather parameters that are critical for Schiphol operation are:

Strong winds
Unlike HiRLAM, the non-hydrostatic model HARMONIE explicitly resolves vertical convective motions. As a result, extreme wind events such as downbursts (e.g. at July 14th, 2010: wind speeds up to 100 km/h, gusts up to 140 km/h) are more realistically captured by the model than with HiRLAM. Also the higher spatial resolution of HARMONIE (1 – 2 km versus 10 km in HiRLAM) results in a more detailed picture of the wind. In general, HARMONIE can represent small regions with very high wind speed, which are mostly absent in HiRLAM (cf. figure 4.6). Finally, if we compare the current operational model HiRLAM with HARMONIE, we also see that in cases where HiRLAM performs well, such as large synoptic scale storms (order 1000 km), HARMONIE gives similar results, but at a higher resolution and with more detail.

Fog
Compared to HiRLAM, HARMONIE seems better capable to predict the dynamical structure of fog fields and of extremes in cloud water at the lowest model levels. Nevertheless, case studies of radiation fog events have revealed that HARMONIE, among other models, has difficulties in forecasting the precise onset and development of the fog layer. A high vertical resolution in the lowest few hundred meters of the model appears to be of great importance. A lower vertical resolution leads in general to a delay in the onset. However, this conclusion should be drawn with care as the number of cases that have been studied is small and in some of the cases we have seen that not all important model parameters improve with an increase in the vertical resolution of the model.

Low clouds
Despite that in general also low clouds are better captured within HARMONIE, stratocumulus clouds are often underpredicted by the model (cf. figure 4.15) due to their relative shallowness (they are only a few hundreds of meters thick). The coarse vertical model resolution makes that these clouds may only be present in the model at 1 or 2 model layers. This makes its representation much more sensitive to small errors. For example, errors of the order of 0.1 °C in temperature may already make the difference between a clear atmosphere and one that is filled with low clouds. Therefore, as with the prediction of fog, also the prediction of the formation of low clouds will likely benefit from a finer vertical model resolution.

To verify this hypothesis, a similar experiment was performed with a very high-resolution (order 10 m) large-eddy simulation (LES) model. It was shown that such a model is well capable to predict the stratocumulus cloud layer (cf. figure 4.16). Due to its fine resolution, these LES models, however, are computationally too expensive for operational use.

Intense precipitation
Several case studies have shown that HARMONIE predicts well heavy precipitation and the general shape of rainfall patterns. Rainfall intensity and the timing of precipitation, however, seem to be highly sensitive to the size of the computational model domain (cf. figure 4.9). For smaller model domains the onset of the precipitation is often too early and the intensity is too low. To be able to run the high-resolution model HARMONIE with confidence, producing reliable results but at the same time keep the computational load within acceptable limits, a domain size of 400x400 grid-points, using the standard horizontal resolution of 2.5x2.5 km, is recommended. This is necessary for the development of convective structures by the model, such as storms and squall lines. This domain size ensures that HARMONIE does not only add smaller scale information to HiRLAM, but can really employ the benefits of a non-hydrostatic model to yield a state-of-the-art prediction.

The impact of climate change
For a few case studies HARMONIE has been applied to study the effect of increased sea surface temperature on rainfall amounts and winds. It was found that this effect was most easily noticed for weather systems that approach from the west, i.e. overseas, and that have enough time to exert its influence. The main effect for weather systems approaching from the sea seems to be that convection close to the coast is triggered more easily, rainfall patterns change and coastal rainfall amounts and winds are more intense.

HARMONIE has also been applied to study the urban heat island effect of Rotterdam. An urban heat island is a metropolitan area that is significantly warmer than its surrounding rural areas. HARMONIE is able to model this effect by using a town energy budget module. This module calculates the effect of the built up environment and landscape heterogeneity on local weather conditions, such as e.g. the 2m temperature. It appears that the results of high-resolution models such as HARMONIE are very sensitive to the land-use classification data that is used by the model. This will also be of importance for the modelling of other local weather phenomena that are affected by the heterogeneity of the surface, such as e.g. convective rainfall.

We also evaluated HARMONIE for its skill to predict monthly precipitation amounts during the summer. To this purpose the August 2006 period was evaluated. In this period a record amount of precipitation was observed, particularly near the coast where amounts exceeded 300% of the climatological mean (cf. figure 5.3). For this study HARMONIE has been applied in two different modes: a) Hindcast mode in which consecutive daily weather forecasts are made that start each day from the ECMWF analysis, and b) Climate mode in which the model is initialised only once at July 31 running continuously until the end of August. Both models use the same boundary conditions, in this case the ECMWF analysis. The hindcast results are indicative for what we can expect from HARMONIE when used as an operational weather prediction model. The climate mode runs are indicative of how HARMONIE would perform as a regional climate model, in this case fed with perfect boundary conditions.

The results show that both the climate and hindcast simulations overpredict the monthly precipitation by around 15% (cf. table 5.1). Both model simulations predict the qualitative picture of more precipitation in the coastal regions than inland in agreement with the observations. However, inland precipitation is overestimated and the peak value of the hindcast run near the coast is much too high (cf. figure 5.6). Further research has revealed that the most likely reason for the higher precipitation amounts in HARMONIE is a much too high surface evaporation (cf. figure 5.7) caused by too high soil moisture values in the model.

It is believed that the higher amount of rainfall, as observed in August 2006, is caused by higher sea surface temperatures (SST). To investigate the role of the SST on enhanced precipitation, two additional climate runs were made with increased (+2K) and decreased (-2K) SST. It appears that changing the SST has a strong influence on the monthly precipitation and that the most significant differences occur in the coastal zone (cf. table 5.2 and figures 5.8 and 5.9). Higher SST's indicate a greater amount of rainfall in the coastal area, but inland more than 100 km from the coast the SST has no effect. It also appears that the models benefit from high-resolution SST fields based on NOAA satellite observations. This has been demonstrated with RACMO hindcasts (cf. figure 5.11), because it is technically not yet possible for HARMONIE to use these high-resolution SST's. In the operational setup of HARMONIE, the use of these SST's is strongly recommended.

Finally, a few new verification methods have been studied, which we believe are more suited to demonstrate the skill of high resolution models such as HARMONIE, especially for precipitation forecasts. The new methods try to circumvent the 'double penalty' problem that conventional verification methods suffer from, for example: a shower is forecasted where it is not observed, raising a 'false alarm', and the observed shower is not forecasted, counting as a 'miss'. The application of these methods for HARMONIE will be further investigated in the 2nd tranche of the KfC programme.

1 Introduction

1.1 Hotspot Schiphol Mainport

Schiphol Mainport and its network of international connections are of vital importance for the Dutch economy. Schiphol is a primary hub for Air France – KLM in the region, resulting in a strong economic position for the Netherlands in Europe and in many employment opportunities. The airport and the surrounding area are vulnerable to changes in our climate. The airport is situated 4–6 m below sea level in the Haarlemmermeer, one of the most complex and vulnerable urban areas of the world. An accelerated sea level rise together with continuous land subsidence and periods of intense precipitation and drought, forces Schiphol to investigate which adaptations are necessary to make the airport and the whole Schiphol region "Climate Proof".

Figure 1.1: *Aerial view of Schiphol Mainport in Amsterdam the Netherlands (source: guardian.co.uk).*

Climate proofing Schiphol and to contribute to a sustainable airport operation, now and in the future, requires knowledge on various issues that may be affected by climate change: 1) On regional issues such as land-use, infrastructure, housing, flight safety, noise, air pollution and water management, and 2) On the local weather conditions at the airport which have a direct influence on the airport capacity, which is of vital importance for the position of Schiphol and is a limiting factor for a possible future expansion of the airport. In Hotspot Schiphol Mainport we focus on the effect that climate change has on the local weather conditions at the airport. The objectives of the Hotspot are:

1. To develop a Wind and Visibility Monitoring System for critical weather conditions in the changing climate at the airport (Project *"WindVisions"*)
2. To provide tailored information about the current local climate at the airport and the perceived changes in climate in the past decennia (Project *"Climatology and Climate Scenario's Mainport Schiphol"*)
3. To provide and demonstrate new innovative model tools that can be used to compute with sufficient accuracy the effect that climate change has on the local critical weather conditions at the airport (Project *"Impact"*)

1.2 Problem definition

Adverse weather highly impacts safety and efficiency in aviation. Recent studies showed that in about 20% of aviation related accidents involving aircraft and in about 80% of airspace delays, the weather was a cause or contributing factor [FAA, 2010; Eurocontrol, 2007].

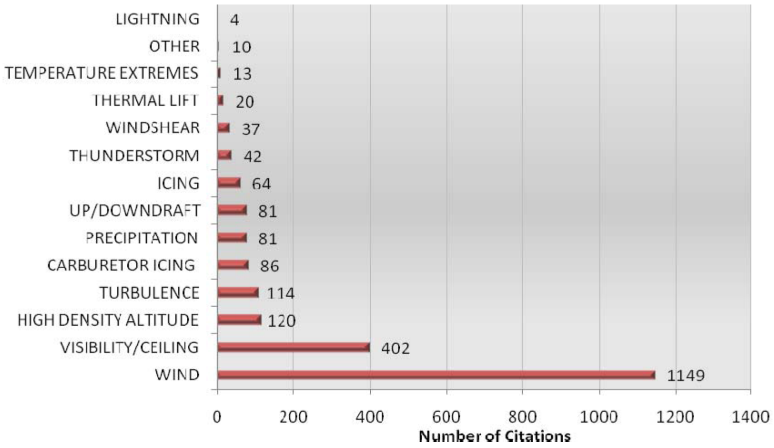

__Figure 1.2:__ Weather factors and their number of occurrences (not mutually exclusive) that cause or contribute to weather-related aviation accidents (source: FAA, 2010).

Schiphol requirements

Due to its location near the sea, the weather at Schiphol airport is often adverse and subject to sudden changes. Critical weather conditions, like fog, low clouds, stormy winds, severe thunderstorms and heavy precipitation, lead to a loss in the available airport capacity, and if not foreseen in time, to additional delays, diversions and holdings, resulting in increasing costs. For example, at Schiphol airport the number of arrivals and departures reduces by a factor of at least 1.5 when visibility is less than 550 m or when cloud ceiling is less than 200 ft. To increase safety and guarantee operational efficiency during flight and platform operations at the airport, accurate and reliable information on critical weather parameters and their changes on local scales are needed. This will be even more pressing when in a future climate adverse weather occurs more often, is more intense and is due to more sudden changes.

Schiphol problem caused by climate change

The impact of climate change on Schiphol airport is determined by the effect that the future weather has on the airport operation. To guarantee a sustainable and reliable operation of the airport in a future climate, we should be able to identify and quantify changes in the frequency and intensity at which critical weather conditions at Schiphol airport will occur with sufficient accuracy. The main problem however is that we do not know how climate change affects the weather on local scales. Specific questions related to the Schiphol situation are:

- How will local precipitation extremes at Schiphol airport change when air temperature and sea-surface temperature increase in a future climate?
- How will changes in our climate, changes in the physiographic properties of the landscape (such as land-use, vegetation and soil type), or changes in spatial planning, affect the local weather conditions at the airport for parameters such as wind, low clouds and fog?

Present day climate models show that extreme weather events, such as heavy summer rain showers and long periods of heat and drought, become more intense. But, it is still poorly understood how short-duration showers will grow due to temperature increase and our abilities to model rainfall processes in our models are limited [Lenderink et al., 2008]. One of the most important reasons for this are that our climate models do not provide enough spatial differentiation to describe the effect that climate change has on the local weather, and changes in weather extremes are highly uncertain. Shortcomings are due to a coarse resolution of the model, a poor physical description of the land-atmosphere interaction, and the limited predictability of local events.

1.3 Research objectives and approach

In Impact we introduce the new high-resolution (1 – 2 km) non-hydrostatic atmospheric model HARMONIE as the next generation weather and climate model. In the project we demonstrate the potential of this model to better quantify and understand the effect of global climate change on the weather parameters and the scales that are relevant for Schiphol airport. This model, which has been developed by a cooperation of the meteorological institutes of 27 European and North African countries, is our next generation model for operational weather forecasting and weather research on the smaller scales (the so-called mesoscale). Moreover, a few countries also use the model for regional climate research. In the Impact project we intend to do both.

The main objectives of Impact are:

1. To demonstrate the potential of HARMONIE to provide an improved and more detailed short term weather prediction for Schiphol airport;
2. To demonstrate how HARMONIE can be used to compute the effect of climate change on local critical weather conditions at Schiphol airport;

Our approach

Impact is primarily a demonstration project. By selected case studies we will first demonstrate the ability of HARMONIE to determine local high-resolution weather forecasts for Schiphol airport, in particular for those meteorological circumstances that may hinder aircraft operations. Next, we will demonstrate how certain extreme weather events would evolve in case of changing climatological circumstances. The potential of the HARMONIE model to provide high-resolution weather forecasts for Schiphol airport is assessed in the project for several cases in our current and past climate. For this purpose, the model output is validated against the coarse-resolution (10 – 20 km) hydrostatic HiRLAM model, which is the current operational weather prediction model for Schiphol airport, and against local airport observations.

Knowledge from the Impact case studies will be used to further adapt and improve the HARMONIE model. The implementation of these improvements, i.e. harvesting of the results of Impact, is foreseen in the follow-up phase of Impact (2nd tranche KfC programme). In the Impact project we will setup a strong knowledge infrastructure at all partner sites, which is needed for that.

Stakeholders and scientists involved

In Impact stakeholders from the Schiphol Group (AAS) and the Air Traffic Control in the Netherlands (LVNL) are involved. These stakeholders have a strong interest in learning how climate change affects the critical weather conditions at the airport. Furthermore, they expect that Impact will contribute to the development of model tools that can be used to provide improved and more detailed weather forecasts for the airport. Their own adaptation and operational decision strategies highly depend on that. The stakeholders play an important role in the Impact Inventory, in which an overview of local weather parameters that impact the airport operation, their order of relevance and the corresponding "safety" thresholds, will be determined. This inventory helps us to better understand the needs of Schiphol operations for weather information in our present and future climate. Furthermore, it provides more insight in which parameters to retrieve from our models to derive the required information.

The Impact research team consists of scientists from KNMI and from the Dutch universities of Wageningen and Delft. KNMI scientists are involved due to their experience in operational weather forecasting and weather and climate research. Scientists from Wageningen and Delft are involved due to their expertise on local weather processes and their interest to use the newly developed HARMONIE model for general research and for specific research focussing on Schiphol airport. One of the objectives of Impact is to build up a strong knowledge base at these partner sites as well.

In order to facilitate the cooperation between the scientists, Impact will provide a so called "academic" version of the HARMONIE model, which can easily be used at KNMI and various Dutch universities for weather and climate research on basic high-resolution weather parameters, such as those needed for Schiphol airport. For the development of such an academic version, Impact will cooperate with scientists from the international HiRLAM-ALADIN program.

1.4 How to read this report

This is the final report of the KfC project Impact. This report is partly based on the work package reports ***Impact Inventory, Impact HARMONIE Cases and Impact Cobel Verification***, which can be downloaded from the Impact website (cf. the references in section 8). In the work package reports the user requirements are presented in detail. Furthermore, the results from all our HARMONIE model case studies and some verification results for the site-specific fog model Cobel are presented. In this report we concentrate on the most important user requirements from the stakeholders (chapter 2), on an introduction to the next generation weather and climate model HARMONIE (chapter 3), on a demonstration of the applicability of HARMONIE for present and future weather case studies (chapter 4), on a demonstration of the use of HARMONIE for climate research (chapter 5), on a presentation of some standard verification results of the current HARMONIE version, including a proposal for a new verification approach which is more suited for high-resolution models such as HARMONIE (chapter 6), and finally on a summary of the most important findings and recommendations for future work (chapter 7).

2 Schiphol Inventory

An important part of the Impact project is the Inventory. The purpose of this inventory is to identify those weather parameters that highly affect Schiphol operation, their order of importance (ranging from low to high), their corresponding "safety" thresholds for several users at the airport (so called user risk profiles) and how those weather parameters can be observed and retrieved from our weather prediction and climate models at its best.

The Inventory describes the present and future needs of the stakeholders at Schiphol airport for local weather information. Stakeholders involved in the Inventory are the Schiphol Group (AAS), Air Traffic Control the Netherlands (LVNL) and KLM airlines. KNMI has a long-term relation with these stakeholders as a provider of operational weather information for aeronautical purposes. For the whole Inventory we refer to the Inventory report [Jacobs et al., 2011]. This chapter gives a short summary of the most critical weather parameters for Schiphol airport and how its corresponding forecasts are used for collaborate decision making at the airport.

2.1 Critical weather conditions at Schiphol airport

According to the Impact Inventory, the following weather parameters, and sudden changes in these, are most critical for Schiphol operation:

1. Wind direction, wind intensity, wind shear, wind fluctuations (gusts)
2. Surface visibility (VIS/RVR) and low clouds (Ceiling): see table 2.1
3. Precipitation intensity and type (snow, hail, rain, freezing rain)
4. Specific weather conditions such as thunderstorms, lightning, up- and downdrafts
5. Surface and upper-air temperature

Figure 2.1: *Snow (left) and hail (right) are weather phenomena that cause a lot of damage to airport operation and aircraft.*

In the case studies that have been performed with HARMONIE, we mainly focus on wind, surface visibility, low clouds and precipitation. These weather parameters are critical and of common interest to all stakeholders the airport.

Wind

For safety and efficiency, airplanes should maximize their possibility to land and take-off against the wind. But, this is not always possible due to the existing runway orientation and due to sudden wind variations. In practice, airplanes often operate under crosswind and sometimes tailwind conditions. For safety, cross- and tailwind values are restricted to certain limits. Depending on the condition of the runway, these limits are 20 knots for crosswind and 7 knots for tailwind. In these limits sudden fluctuations in the wind (gusts) of 10 knots and more are included. When crosswind limits are exceeded and there are fewer runways available that are parallel to the wind, this will reduce the available operational airport capacity. This happens for example at Schiphol airport during strong southwesterly winds.

As Schiphol airport is located near the sea, the wind is often adverse and subject to sudden changes. In order to reduce the negative effect that the wind has on the available operational airport capacity, Schiphol airport is equipped with 6 runways at different wind rose orientations (see figure 2.2). To reduce the adverse effect of wind and wind change on operations, accurate forecasts are needed for periods when cross- and tailwind components exceed their limits near the touchdown and take-off positions at the runways.

Figure 2.2: *Runways and their corresponding wind rose orientations at Schiphol airport.*

Surface visibility and low clouds

Visibility refers to the greatest horizontal distance at which prominent objects can be viewed with the naked eye. Visibility is affected by weather conditions such as precipitation, fog and haze. Similar to surface visibility, the airports view from above is obscured by the presence of low clouds when their coverage is at least 5 okta, or 62.5%. In aviation the minimum height of these clouds is called the ceiling. Adverse visibility conditions have a direct negative influence on the available operational capacity. For example, at Schiphol airport the number of arrivals and departures reduces by at least 30% when visibility is less than 550 m or when cloud ceiling is less than 200 ft (cf. table 2.1).

Accurate information on the time of onset and cessation of reduced visibility conditions will allow for a more efficient use of the available airport capacity. This requires accurate forecasts of visibility and low clouds, of their spatial variability and temporal fluctuations at the airport.

Table 2.1: *Visibility classifications (including the corresponding thresholds for visibility and ceiling) and the impact of low visibility conditions on airport capacity.*

Visibility classification	Visibility [VIS/RVR]*		Ceiling*	Capacity restrictions due to visibility (movements / hour)
Good	> 5 km [VIS]	and	> 1000 ft	68 arrivals or 74 departures, max 104/108 movements No flow restrictions
Marginal	1.5 – 5 km [VIS]	or	300 – 1000 ft	68 arrivals or 74 departures, max 104/108 movements. Use of independent parallel runways required. No flow restrictions
LVP phase A	550 – 1500 m [RVR]	or	200 – 300 ft	56 arrivals or 52 departures, max 80 movements In general no flow restrictions
LVP phase B	350 – 550 m [RVR]	or	< 200 ft	44 arrivals or 52 departures, max 74 movements Flow restrictions in force
LVP phase C	200 – 350 m [RVR]			30 arrivals or 17 departures, max 47 movements Flow restrictions in force
LVP phase D	< 200 m [RVR]			16 arrivals or 20 departures, max 36 movements Flow restrictions in force

* RVR = Runway Visual Range; VIS = Visibility for aeronautical purposes; Ceiling = Height of lowest cloud layer with minimum coverage of 5 okta (62.5%).

Precipitation

Extreme precipitation amounts at Schiphol airport may lead to flight restrictions when the rain will accumulate at the runway surface. This will happen when the rain intensity is more than 8 mm/hour for at least 15 minutes. Besides rainfall, also snow, hail and freezing rain (or rain on frozen undergrounds) may lead to either increasing costs, due to damage or suppression of icing conditions, or to the enforcement of flight restrictions. At present, short-term predictions of extreme rainfall, such as heavy summer showers, are too uncertain to base operational decisions on that. Improved forecasts are urgently needed.

2.2 Collaborate decision making at Schiphol airport

Operational weather forecasting and subsequently decision making at Schiphol airport, is heavily based on the output of Numerical Weather Prediction (NWP) models. For short-term forecasts, i.e. up to 48 hours ahead, currently the operational HiRLAM model is used for that. During the next years, this role will be taken over by the high-resolution NWP model HARMONIE. We expect that the HARMONIE model will show significant improvements with respect to the description of local wind fields, the exchange of moisture and heat between the atmosphere and the earths surface (which is relevant for the formation and cessation of fog and low clouds) and the development of convective summer rain showers that may lead to intense precipitation amounts and very strong winds. In chapter 4, the potential of the model to do this will be demonstrated.

The NWP model forms the hearth of the operational weather prediction chain. Sometimes model output needs to be further post-processed, for example to determine parameters that are not outputted directly by the model (such as e.g. the precipitation type in the HiRLAM model or indicators for aircraft induced lightning) or when the customer requires probabilistic forecasts instead of deterministic model output.

The weather forecasts and their impact on airport capacity are discussed several times a day during a briefing (video conference) between the operational divisions from LVNL, AAS and KLM, and KNMI as the weather provider. Based on the outcome of these briefings, LVNL makes a capacity forecast for the airport and sends it to AAS and KLM.

KLM approach for capacity prognoses

Besides the above-mentioned briefings, KLM also uses a Capacity Prognoses System (CPS) to determine the airport capacity. In this system (cf. figure 2.3), probabilities on reduced visibility, low clouds and winds, or deterministic values from the NWP model including information about its spread, are used, together with runway availability, runway preference and runway capacity, to determine a probabilistic capacity prognosis. In figure 2.4 an example of such a capacity prognosis is given. The present CPS model is a simplified version of reality, which has been developed as a prototype by KLM. The model still has to prove its value for use during daily operations. Operational measures are never based on the outcome of this model alone. The stakeholders at the airport aim to develop a joint capacity forecast system that can be used by all parties at the airport.

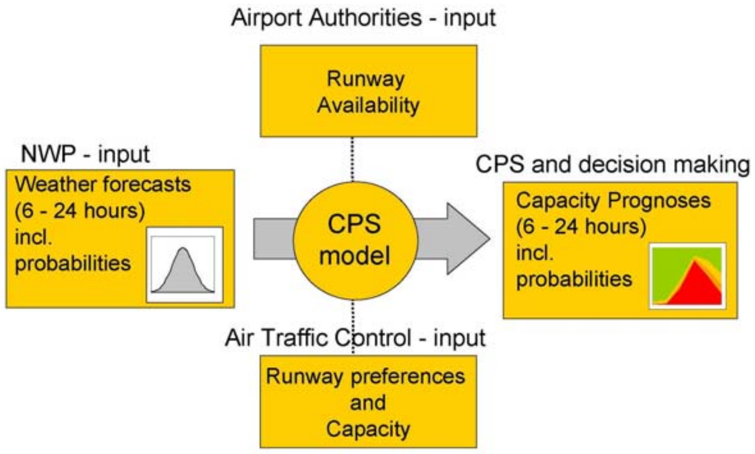

Figure 2.3: *Coupling of weather information to runway information (runway availability, preference and capacity), in the Schiphol Capacity Prognoses System (CPS).*

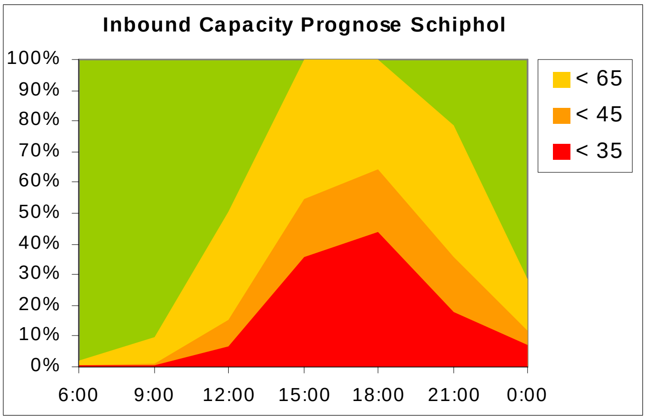

Figure 2.4: *An example of a probabilistic forecast for reduced inbound capacity during a morning peak at Schiphol airport. The probability is given that the number of landings (i.e. arrivals) is below a certain threshold. The thresholds are 35, 45 or 65 arrivals per hour.*

3 A scientific revolution on weather and climate modelling

3.1 Weather conditions on local scales

Surface weather variables, boundary layer structures, wind, clouds and precipitation, are substantially driven by local physiographic properties and by the heterogeneity of the landscape. Our present day weather and climate models display relative poor skills to compute these conditions, especially in critical situations when the weather is often intense and the spatial and temporal scales of the weather structures are small. The most important reasons for this are that the models are hydrostatic and have a coarse resolution, that the description of physical land-surface and boundary layer processes in the models is poor, and that a local high-resolution observing network, needed to validate the model and to compute an accurate initial state for a weather prediction model, is missing. These shortcomings make that the models are inadequate to numerically resolve most of the key physical processes that lead to critical local weather conditions such as heavy rain showers, local winds, and the formation and decay of fog and low clouds.

3.2 Next generation non-hydrostatic modelling

To be able to compute the effect of climate change on the critical weather conditions at Schiphol airport with sufficient accuracy, we need a weather analysis and prediction model with a spatial resolution of 1 – 2 km. Numerical Weather Prediction (NWP) at such a high resolution requires a complete metamorphosis of the model on model dynamics, model physics and model analysis. During the last 10 years, intensive research has brought increased knowledge on all these issues. A non-hydrostatic treatment of model dynamics enables us to explicitly resolve vertical (convective) movements in the model [Kato, 1997]. This is necessary for explicit simulation of small-scale clouds. A consistent treatment of sub-model-grid processes has led to a unified approach for the physical parameterization of clouds, turbulence and convection in the atmospheric boundary layer of the model [Siebesma et al., 2007; Neggers et al., 2008]. New generation observing systems such as the Meteosat and Metop satellites *(www.eumetsat.de)* and high quality wind profiles from Doppler weather radars [Holleman, 2005] enable us to observe the state of the atmosphere with much higher spatial and temporal resolution. New data assimilation techniques are presently being developed that enables us to incorporate these observations in NWP models, with the purpose to improve the analysis of our model fields [Seity et al, 2011]. Furthermore, these measurements can be used for model validation as well.

The newly achieved knowledge is presently being implemented by a large European and North African consortium (the “*HiRLAM-ALADIN collaboration*”, see figure 3.1), in the next generation non-hydrostatic NWP model, named HAR-

MONIE. In Impact the potential of the HARMONIE model to compute high-resolution local weather forecasts for Schiphol airport and to determine changes in critical weather conditions at the airport as a result of climate change are shown. The use of HARMONIE within this context has several advantages:

1. HARMONIE will be the next generation weather analysis and forecasting model, and will be used operationally by a large number of European national meteorological services;
2. HARMONIE contains a data assimilation module that can be used to incorporate observations and compute analysed model fields, which are suited for the monitoring of weather and climate related variables;
3. The HARMONIE consortium will take care that the model can be used under various circumstances and for extreme weather conditions. The model will be supplied with a quality label;
4. The ECMWF (European Centre for Medium-Range Weather Forecasts) will develop a non-hydrostatic forecast model along the same lines as HARMONIE;
5. HARMONIE and ECEARTH both use as system environment IFS (Integrated Forecast System), which enables a future integration of both models in the “Climate Knowledge Facility (CKF)” of the KfC programme;
6. The Rossby Centre at the Swedish meteorological institute (SMHI) has setup a climate branch of HARMONIE. Within this branch the HARMONIE system is developed and evaluated for regional climate applications.

3.3 HARMONIE and HiRLAM – model characteristics and differences

In order to judge the quality of the HARMONIE model for numerical weather prediction, our current operational weather prediction model HiRLAM is used as benchmark. In Impact both models are used for performing the numerical simulations. For details on the models, e.g. precisely which physical parameterization schemes are used and how initial and boundary conditions for the models are derived, we refer to their online documentation on www.hirlam.org.

HiRLAM is a hydrostatic grid-point model, of which the dynamical core is based on a semi-implicit semi-Lagrangian discretization of the multi-level primitive equations, using a hybrid coordinate in the vertical. Being hydrostatic means that the hydrostatic approximation replaces the vertical momentum equation. In other words, vertical acceleration is neglected compared to vertical pressure gradients. This is a good approximation for the synoptic and sub-synoptic scales of motion (horizontal length scales of 100 ~ 1000 km). The consequence of using this simplification of the model equations is that certain features cannot be modelled anymore, such as acoustic sound waves and strong vertical winds in heavy thunderstorms and tornado like events, and winds near obstacles and mountains. It also limits the usefulness of such models in situations of severe weather. Nevertheless, hydrostatic models have been successfully applied with horizontal resolutions as small as about 10 km and resolving even some circulations at the mesoscale (horizontal length scale of 2 ~ 200 km). The horizontal resolution of 10 km is computationally feasible because the HiRLAM model is a so-called Limited Area Model (LAM). For its model runs it depends on data provided at the boundaries of the model integration domain. This data is usually produced by model runs at a coarser, say 30 km, resolution. The prognostic variables of HiRLAM comprise horizontal wind components u, v, temperature T, specific humidity q and pressure p.

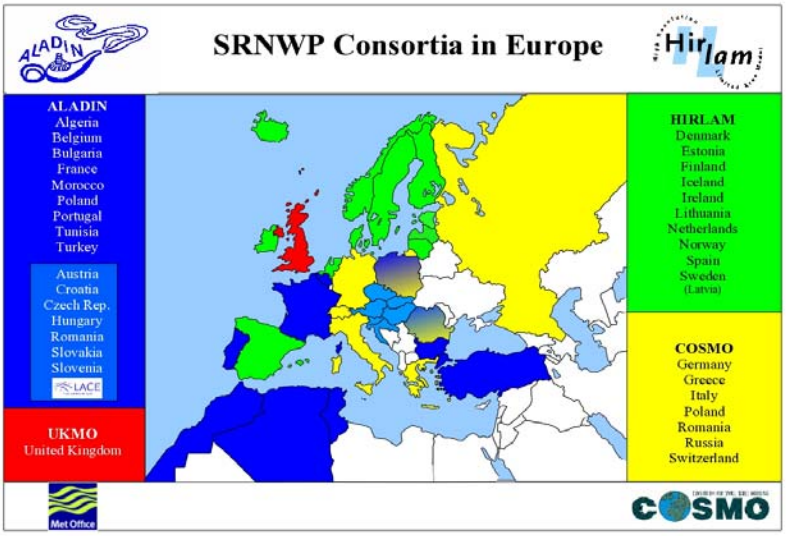

Figure 3.1: *HiRLAM and ALADIN among the four large consortia of Short Range Numerical Weather Prediction (SRNWP) in Europe.*

For cases of severe weather, such as strong convection events and mountain waves, the hydrostatic approximation often breaks down. High-resolution models, which are being developed to initiate and evolve such events accurately, therefore usually solve the vertical momentum equation explicitly. These non-hydrostatic models as they are called can be successfully used for weather forecasting on horizontal scales of the order of 100 m, thereby resolving small-scale mesoscale circulations such as cumulus convection. The HARMONIE model used in this study is such a non-hydrostatic model. It is being developed by the HiRLAM and ALADIN collaboration (see figure 3.1). The dynamical core of the model is based on a two time-level semi-implicit semi-Lagrangian discretization of the fully elastic equations, using a hybrid coordinate in the vertical.

Although details of the HARMONIE model formulation can be found on www.hirlam.org, we briefly mention some of the most important components:

- First of all, the HARMONIE model is equipped with an advanced convection scheme (EDMF), which combines small-scale turbulent and larger-scale convective transport in one consistent framework. This mass flux scheme [Siebesma et al., 2007; Neggers et al., 2009; De Rooy and Siebesma, 2008], in which the lateral mixing plays an important role, does indeed improve the specific humidity vertical profiles as expected. Together with a recently improved cloud scheme already quite realistic examples of cloud formation have been observed in HARMONIE runs (figure 3.2). Since there are still many opportunities to improve upon the EDMF scheme, these encouraging results are quite promising for various critical aspects of weather forecasting, such as, fog formation.

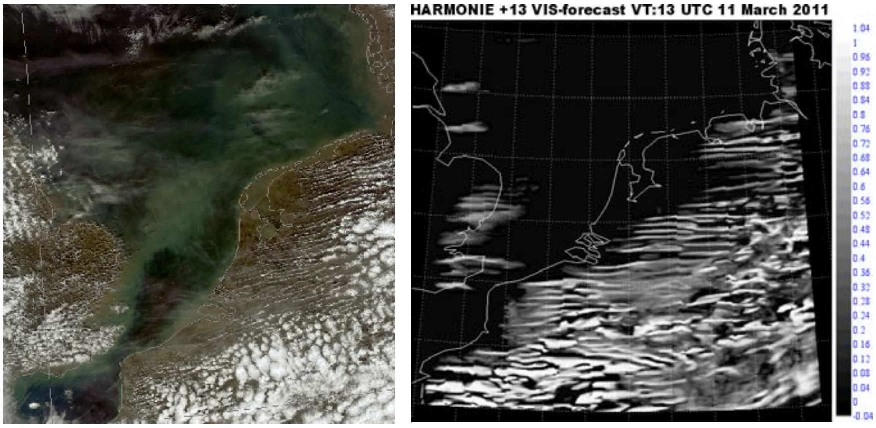

Figure 3.2: *Cloud streets observed by satellite (left) and computed by HARMONIE (right).*

- Another important component of HARMONIE is SURFEX, the model that handles surface and soil processes. It comprises of several modules, such as a 1-D high-resolution column model CANOPY to associate the boundary layer with the canopy [Masson, 2008] and the so-called Town Energy Budget (TEB) urban canyon model [Masson, 2000]. The latter TEB model is essential in taking into account the impact of urbanization on the local meteorological properties.

- Finally, there is an advanced microphysics package, which is fully integrated in HARMONIE. It describes the dynamics of and interaction between the various hydrometeors, such as, specific humidity, snow, graupel, cloud ice, cloud water and in due course hail. Being part of the model formulation, these hydrometeors can be directly outputted, without additional post-processing such as in the HiRLAM model. Numerical experiments have shown that this model component in particular plays an important role in the predictability properties of the model. For example, tuning of the evaporation rate may drastically change the location and amplitude of precipitation fields [Barkmeijer, 2010].

There is yet another important component of the HARMONIE forecasting suite, which is not used in the current study though. This concerns the data-assimilation module, which in combining available observations with a short-range (6 hour) forecast yields the most optimal starting point, the so-called analysis, for the forecast. In the case studies presented in this report, the model starts from analyses produced by other weather prediction models at a coarser resolution. Research is under way of how to adapt the data-assimilation module in order to make fully use of observational data at the mesoscale. One of the directions, which are currently being explored, is the assimilation of radar data. If successful it will enable a much-improved initialisation of the forecast in areas with, but also without, precipitation. Given the ongoing research activities with HARMONIE, it is evident that during the coming years there is a real opportunity to engage in the exciting area of mesoscale meteorology.

4 Present and future weather modelling with HARMONIE

4.1 Selected case studies

In this chapter we show whether the HARMONIE model is capable to provide more detailed and more accurate weather predictions for Schiphol airport than our present day operational weather prediction model HiRLAM. For this study HARMONIE model data is simulated for a selection of weather case studies (cf. table 4.1) and compared to local weather observations and to model output from HiRLAM[1]. The selected case studies represent adverse weather conditions for weather parameters that are most critical for Schiphol operation. We retrieved these weather parameters from the Impact Inventory (cf. chapter 2). The corresponding model parameters that we validated are: precipitation intensity and type, strong winds or wind shear, strong vertical winds, low clouds, and in case of fog, cloud water at ground level, to predict visibility at the surface. Observations that are used for validation are e.g. precipitation radar images, satellite images, wind speed measurements and local observations at the airport. In this chapter we distinguish between the weather in our present climate *(present weather)* and the weather in our future climate *(future weather)*. For the latter, we have studied how some of our cases would evolve in a future climate, due to changes in the climatological circumstances, such as e.g. an increase in sea-surface temperatures. In this chapter we will demonstrate the results from some of the cases that we studied. More results can be found in [van der Plas, 2011; Ronda et al., 2012; Mendez-Gomez et al., 2012].

Table 4.1: *List of HARMONIE case studies selected for Impact. The cases in blue are presented in more detail in this chapter.*

Date	**Type of situation**	**Remarks**
	Fog and low clouds at Schiphol airport	
April 8 and 9, 2009	Due to the passage of a warm front in northeasterly direction over the Netherlands, radiation fog develops at Schiphol airport, followed by advective fog and low stratus clouds.	HARMONIE compared to WRF.
April 1, 2009	Fog and low stratus clouds at Schiphol airport due to the presence of a persistent stationary warm front.	
October 5 and 6, 2005	2 diurnal cycles of radiation fog in the southwest part of the Netherlands.	HARMONIE compared to WRF.
November 24 and 25, 2004	2 diurnal cycles of radiation fog, with extreme dry air loft, and temperatures below 0 °C.	107 flights cancelled at EHAM. HARMONIE compared to WRF.

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[1] For some case studies, for example for the simulation of radiation fog events, also the American research model WRF has been used for comparison [Skamarock et al., 2005].

Strong convective events		
July 14, 2010	A front that originates from the southwest of France passes over the Netherlands, resulting in thunderstorms with very strong convection (a so-called downburst) and a large amount of precipitation.	During the passage of the front, strong winds and gusts were reported, near the town of Vethuizen, causing substantial damage.
August 13, 2010	Cold air approaching from the North Sea is pushed into the warmer coastal area. Due to convergence along the coastline, convection is triggered leading to severe lightning and intense rain.	
August 20, 2009	Due to the advection of warm air from the south and the passage of a cold front from the west, a mesoscale convective system develops, causing a rain band over the west of the Netherlands. This rain band intensifies and produces thunderstorms with hail.	A weather alarm was issued for heavy gusts.
May 25/26, 2009	An active and fast moving squall line reaches the south of the Netherlands and passes within 2 hours. During this time period heavy thunderstorms, severe lighting, heavy gusts and hail occur in the western part of the Netherlands during early morning.	Weather alarm situation. Wind gusts (29 m/s) and large hail were reported at Schiphol airport. The hail caused damage to the airplanes.
July 9, 2007	A squall line approaches the Dutch coast from the west to northwest. The squall line produces very intense precipitation and strong vertical winds.	Several water sprouts were observed near the coast.
April 30, 2006	Deep convection in a cold pool over the Netherlands with intense precipitation and severe downdrafts.	Strong outflow conditions close to the ground.
Heavy storm and heavy gusts		
January 18, 2007	A heavy storm passes the Netherlands from northwest to southeast, bringing severe precipitation, such as hail and torrential rain, and thunder. Large wind speeds and gusts, especially around the coastal area, but also more inland around Schiphol airport, were observed.	Weather alarm situation. Rapid cyclogenesis leads to large wind speeds and gusts (up to 70 knots) in the coastal area.
Wintery precipitation (snow, black ice)		
February 8, 2007	Heavy snowfall in frontal system, moving from southwest to northeast over the Netherlands, covering the whole country in snow.	A weather alarm was issued for intense snowfall.
Other (clouds, sea breeze, …)		
January 30 – February 1, 2011	An extended stratocumulus cloud deck covers the Netherlands. As the cloud base is very close to the ground surface, this causes a very poor visibility (low ceiling).	It is notoriously difficult for weather prediction and climate models to capture these clouds well.
The impact of climate change		
July 20, 2010	The 20th of July was the last warm day of the summer of 2010. For this day the so-called Urban Heat Island (UHI) effect is demonstrated by running HARMONIE on a resolution of 500 m. Also the effect of different land-use datasets is shown.	
July 14, 2010 August 13, 2010 July 9, 2007	For these convective cases it is studied what the influence of increased sea-surface temperatures is on the rainfall intensity, on rainfall amounts and on the wind.	

Note: It turns out that in some cases the size of the model domain has a significant impact on the quality of the forecasts. This happens especially for convective weather events, such as squall lines and thunderstorms. When such a convective systems is not present in the model domain at initialisation time, it needs time to develop its proper dynamics. The domain size used in the default setup was often too small to give accurate results.

4.2 Method

The main tool used for the case studies is the HARMONIE model code, aiming to produce high quality deterministic forecasts at a resolution of typically 1.0 to 2.5 km. The main difference with HiRLAM is that HiRLAM uses hydrostatic equations, in which meteorologically unstable situations appear more or less instantaneously. The fact that HARMONIE uses non-hydrostatic physics to capture convective movement in the atmosphere should lead to an overall better representation and timing of (thunder) storms and squall lines, where strong vertical winds are possible [cf. Saito et al., 2006; Steppeler et al., 2003].

The HARMONIE model code is the focus of the present state-of-the-art meteorological research, and is being updated on a regular basis. New versions include new routines that are provided, new physical parameterizations for improved forecasts, as technical adjustments to have a more flexible and reliable implementation, necessary to run the HARMONIE suite operationally. The version that is used for the majority of our case studies is cycle 36h1.2, released 29 October 2010, which is supposed to be the first version in which among others a proper, improved, coupling between the upper air and the surface scheme is being taken into account. A few or our cases contain results obtained with 35h1.2, the previous version, but it is not probable that the general conclusions will change when studying the same setup with the 36h1.2 model version.

The initial conditions for the model are derived from the analysis of either the HiRLAM or the ECMWF (IFS) model. No information from a previous run or from data assimilation is used. This type of initialisation is often referred to as a *cold start*. As HARMONIE is a so-called *limited area model*, it needs boundary conditions that are provided by a host model. For this purpose also HiRLAM or the ECMWF model are used. Boundary conditions are provided and integrated in the model every three hours. The default domain that is used for each case is a 300 by 300 grid with a resolution of 2.5 km, centred around the Netherlands. From the initial state the non-hydrostatic core is used to evolve the model equations in time.

4.3 Case 1: Radiation fog followed by advection, April 8 – 9, 2009

Despite the high impact of fog on anthropogenic operations such as aviation, fog forecasting remains one of the remaining challenges in meteorology. The reason is that the occurrence of fog is a complex phenomenon that depends on many processes [Holtslag et al., 1990; Bergot et al., 1994].

Layers of radiation fog usually start at air layers very close to the surface, which is prone to radiation cooling because of the relatively high emissivity of the earth’s surface as compared to cloudless air. It can therefore be expected that the vertical resolution of a meteorological model has an important impact on the skill of an atmospheric model to forecast the occurrence and the development of a layer of radiation fog [van der Velde et al., 2010]. Therefore, the effect of increasing the vertical resolution of the mesoscale model HARMONIE has been performed. Preliminary results of HARMONIE are evaluated using observations taken at the Cabauw measurement facility in the central Netherlands. Also, we compare the preliminary results obtained using HARMONIE to preliminary results obtained using the mesoscale model WRF. Furthermore we studied the use of the state-of-the-art 1D column model COBEL [Bergot et al., 2005; Bergot, 2007] for the numerical prediction of fog and low clouds at Schiphol airport [Sander Tijm and Albert Jacobs, 2011; Mark Savenije, 2011]. This single-column model has been provided for this purpose by courtesy of Meteo France.

Description

On 8 and 9 April 2009, the synoptic situation in the Netherlands was dominated by a high-pressure system that was located in central Europe and a depression that was located on the Atlantic Ocean close to the western Irish coast. The weather map for UTC 0:00 on 9 April 2009 shows that above northern France a warm front was located, while south-east of the Netherlands a cold front was located. On 9 April 2009 the warm front passes in northeasterly direction over the Netherlands.

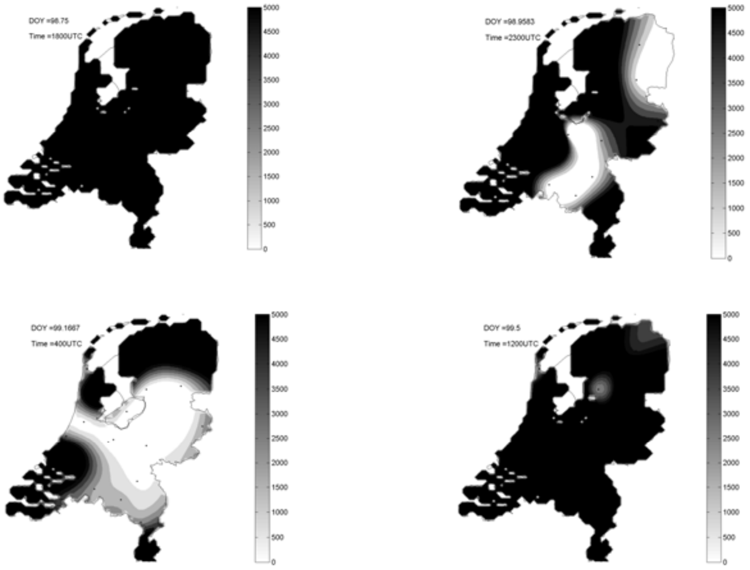


Figure 4.1: *Spatial distribution (spline interpolation) of screen-level visibility (m) as observed at the Dutch meteorological monitoring network in the Netherlands at (top to bottom) 1800 UTC 8 April 2009, 2300 UTC 8 April 2009, 0400 UTC 9 April 2009 and 1200 UTC 9 April 2009.*

The synoptic conditions favoured the development of a fog layer during the early morning of 9 April 2009. The development of the fog layer during the night of 9 April 2009 is illustrated in a visibility map of the Netherlands, which is given in figure 4.1. It shows that at 1800 UTC 8 April 2009, the Netherlands is fog free. At 2300 UTC 8 April 2009 fog starts to appear in the eastern part of the Netherlands (provinces of Gelderland, Noord-Brabant and Groningen). At UTC 0400 9 April 2009 visibility is poor in the central and eastern parts of the Netherlands including the location where Schiphol airport is located. At 1200 UTC 9 April 2009 visibility was good in the entire Netherlands.

Observations

The results of the simulations with both mesoscale atmospheric models are evaluated using data that were gathered at the Cabauw measurement facility [Beljaars and Bosveld, 1997]. The Cabauw measurement facility is located in the western part of the Netherlands (51° 58'N, 4° 56'E).

Observations include measurements of the difference components of the surface radiation and energy budget. To compare the model results to profiles of wind speed, wind direction, temperature and humidity, measurements are used that are taken at different heights along the 200 m tower present at the Cabauw measurement facility. For temperature and the dew point temperature, measurements are available at 2 m, 10 m, 20 m, 40 m, 80 m, 140 m and 200 m.

Model description and model setup

HARMONIE is a non-hydrostatic atmospheric model, which core is developed from the dynamical core of the ALADIN modelling system. HARMONIE solves the fully elastic equations using a semi-Lagrangian discretization in the horizontal and a hybrid vertical coordinate system.

For the HARMONIE simulations version 36h1.3 is used which is available on the server of the ECMWF and can be accessed online. Initial and boundary conditions are taken from the ECMWF model. The domain as specified for this study comprises the Netherlands and consists of an area of 750 km x 750 km centred around the Cabauw tower (51° 58'N, 4° 56'E). Calculations are done on a grid of 300 x 300 grid points with a resolution of 2.5 km x 2.5 km.

Because vertical resolution is expected to be an important factor for the development of a fog layer, we have performed simulations for two different setups of the vertical layering in the model: a vertical layering that matches the vertical layering of HIRLAM (see table 4.2), further called HIR60 in the following and a vertical layering that is called the Meteo-France, further called MF60, which has a much finer resolution in the Atmospheric Boundary Layer (ABL): the lowest model level of MF60 is at about 10 m, while it has six layers in the lowest 200 m (see table 4.2).

Table 4.2: *Approximate height (in m above the surface) of the lowest 8 vertical layers.*

Vertical levels	HIR60	WRF	MF60
1	30	6	10
2	90	14	31
3	152	18	58
4	218	24	93
5	285	32	136
6	353	41	186
7	424	55	243
8	498	70	306

The WRF model is an atmospheric model for modelling processes on the mesoscale [Skamarock et al., 2005]. All simulations performed with the WRF model, are done with the Advance Research Core (ARW, version 3.1.2). For all fog episodes the horizontal grid consists three nested grids with respective resolutions 25 km, 5 km and 1 km. Both the 25 km and 5 km grids comprise of 41 x 41 grid cells, while the finest grid comprises 61 x 61 grid cells. All grids are centred around the Cabauw measurement facility. In the vertical, the configuration of WRF consists of 35 terrain-following vertical coordinates. The lowest model layer is located at about 6 m, while the model has 7 layers in the lowest 200 m (see table 4.2).

For all simulations, WRF has been initialised using ECMWF analysis forecast. Information on vegetation, land-use type, terrain elevation and albedo are obtained from terrestrial data provided by the U.S. Geological Survey (USGS). In the ARW core different physical packages can be selected. In this study we have used the parameterizations that are more or less standard. For the land surface model we have applied the Noah model, which consists of four soil layers with a vegetation layer on top.

For the 8 and 9 April 2009 fog episode simulations are performed for two days starting at 0000 UTC 8 April 2009 and terminating at 0000 UTC 10 April 2009.

Results

Figure 4.2 shows for the fog episode of 8 and 9 April 2009 the observed and modelled net long wave radiation. The net long wave radiation is an important quantity to quantify fog because the liquid water contained in the fog layer is generally a much better emitter of long wave radiation than the air particles that constitute clear air. In the evening of 8 April 2009 both HARMONIE and the WRF permutations show a sharp decrease of the net long wave radiation. The timing of this decrease differs considerably among the different models. In particular the WRF model equipped with the MYJ forecasts a decrease of the net long wave radiation in the evening of 8 April 2009 that is too late and is rather noisy. Both HARMONIE permutations tend to underestimate the net long wave radiation in the evening of 8 April 2009, but they are able to forecast the increase of the net long wave radiation in the morning of 9 April 2009 fairly well.

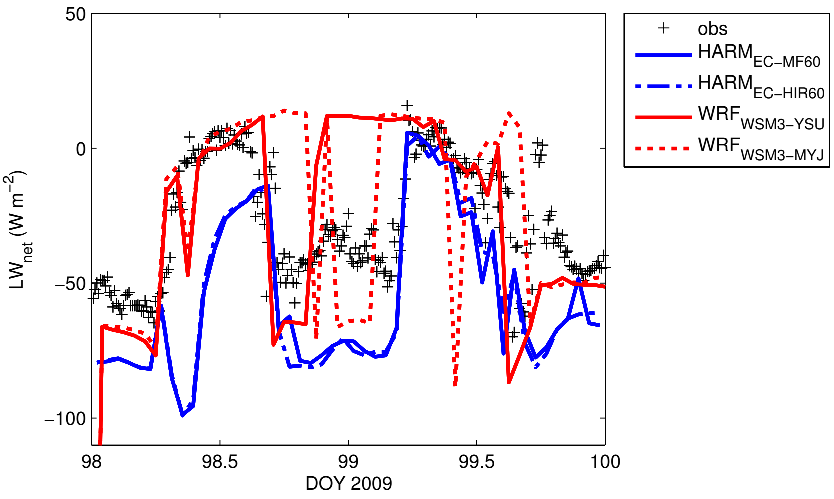


Figure 4.2: *Observed (+) and simulated (blue: HARMONIE, red: WRF) net long wave radiation between 00:00 UTC 8 April 2009 and 00:00 UTC 10 April 2009 for Cabauw.*

On 9 April 2009 both HARMONIE permutations give reasonable estimates of the net long wave radiation. The WRF model equipped with the MYJ scheme forecasts a rather spiky evolution of the net long wave radiation on 9 April 2009. The WRF model equipped with the YSU scheme gives better estimates the net long wave radiation, though it tends to underestimate the net long wave radiation from noon onwards on 9 April 2009.

Figure 4.3 gives for the fog episode on 8 and 9 April 2009 measurements and simulation results for the 2m dew point depression. All models are capable of forecasting the occurrence of the fog layer in the early morning of 9 April 2009. The WRF model equipped with the MYJ scheme gives a good estimate of the time that the fog sets on. The WRF model equipped with the YSU model forecasts an onset of the fog that is too early. The HARMONIE model, particular the permutation that is equipped with the HIR60 vertical resolution, overestimates the dew point depression and forecasts an onset of the fog that is slightly too early. All models are able to simulate a correct timing of the dissolving of fog. After the dissipation of the fog the WRF model equipped with the YSU scheme gives very good estimates of the dew point depression on 9 April. Interestingly, the time at which the observed dew point depression at screen level reaches zero values precedes the time at which the net long wave radiation increases. It appears that until about DOY 2009 99.3 the fog layer is relatively thin. At about DOY 2009 99.3 the thickness of the fog increases sharply which means that the net long wave radiation goes to zero. From about DOY 2009 99.3 onwards the fog layer gradually dissolves leading to a gradual decrease of the net long wave radiation after DOY 2006 99.3. In contrast, the WRF model equipped with the MYJ scheme underestimates the screen dew point depression, whereas both HARMONIE permutations overestimate dew point depression on 9 April 2009 after the dissipation of the fog.

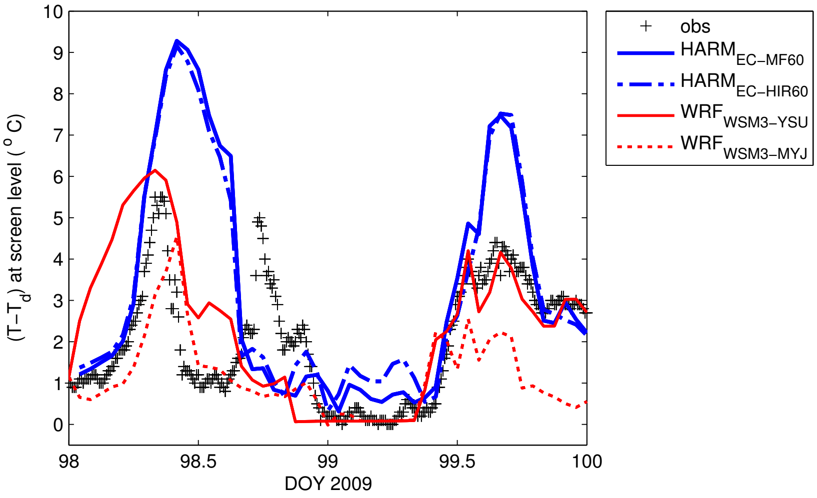


Figure 4.3: *Observed (+) and simulated (blue: HARMONIE, red: WRF) dew point depression at 2m between 00:00 UTC 8 April 2009 and 00:00 UTC 10 April 2009 for Cabauw.*

Conclusion

For three episodes with severe fog in the Netherlands, results obtained by the WRF model and by the HARMONIE model are evaluated. It appears that both models have severe problems in forecasting both the onset and the development of the fog layer. For the fog episode of 8 and 9 April 2009, which is presented here, HARMONIE is able to forecast the onset of the fog layer. Also, it gives rather good estimates of the period during which the dew point depression is close to zero. It however underestimates the dew point depression during the evening of 8 April 2009 and the afternoon of 9 April 2009, indicating that the ABL is very moist as compared to the observations. WRF is able to forecast the development of a fog layer in the morning of 9 April 2009. It forecasts however an onset of fog that is slightly too early as compared to the observations. To forecast fog, finding an optimal vertical resolution in the lowest few hundred meters appears to be important. Overall, the HARMONIE permutation involving the relatively fine MF60 vertical resolution performs better than the HARMONIE permutation involving the HIR60 vertical resolution. This conclusion should however be drawn with care, as some important meteorological parameters such as the 2m temperature and the 2m dew point depression in the afternoon on 5 October 2005 (not shown in this report) are better forecasted using HARMONIE equipped with the HIR60 vertical resolution than using HARMONIE with the MF60 vertical resolution.

4.4 Case 2: Strong convection during passage of a front, July 14, 2010

Description

During July 14th of 2010 a front that originates from the southwest of France passes over the Netherlands. This results in thunderstorms with strong convection and a large amount of precipitation. During the passage of the front, events with strong winds and gusts (probably so-called rear inflow jets) were reported. These events are often accompanied by a so-called ‘hook echo’, a more or less comma shaped line of intense precipitation, visible in the radar images, indicating the presence of a region of very strong vorticity. HARMONIE successfully predicted a structure like this in the eastern part of the country.

Precipitation

Model output from HARMONIE and HiRLAM can be represented in 3D, using the Weather Explorer 3D that has been developed at KNMI [Koutek et al., 2010]. This application allows one to note a few considerable model differences, as shown in figure 4.4. The shape of the simulated clouds in HARMONIE is more realistic, showing the anvil-like shape where the convection collides with the tropopause. In HiRLAM clouds are more or less single columns of water, where no distinction is made between the different phases of the water, and only post-processed as a function of local temperature.

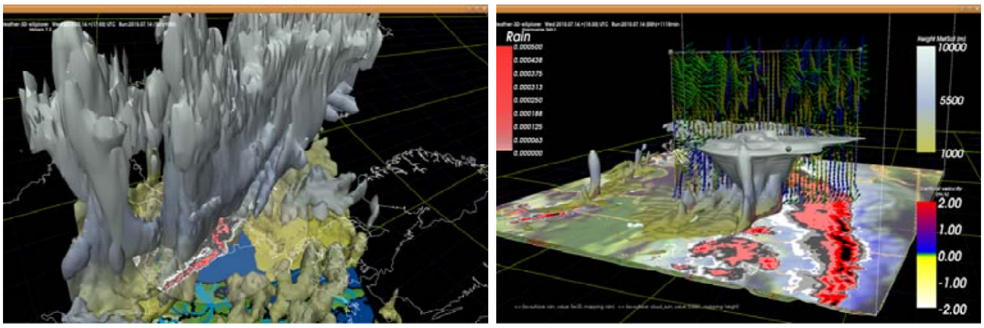


Figure 4.4: *Impressions of HiRLAM (left) and HARMONIE (right) model output in 3D. In grey accumulated cloud water, graupel and ice are presented. The plain, where visible, shows the map and the precipitation radar images.*

When we compare the HiRLAM precipitation forecasts to those obtained with HARMONIE, we can note a couple of differences (cf. figure 4.5). First of all, HiRLAM predicts the region of most intense precipitation between 15:00 and 18:00 UTC at the corner of South Holland (near Hoek van Holland). The frontal structure is not very pronounced. HARMONIE shows considerably more intense bands of rain over the south and east of the Netherlands. Second, HiRLAM produces considerably less rain than HARMONIE. The three hour accumulated rain as shown in figure 4.5 reaches 60 mm, whereas in the HiRLAM forecast not more than 30-40 mm is predicted. If we look at the observations we can look at instantaneous precipitation radar data or at in-situ measurements from the airport. In figure 4.5 a time series plot of precipitation at Schiphol airport is presented. The agreement as shown here is remarkably well. In general, the point-to-point instances of precipitation of high-resolution numerical weather prediction models cannot always be correct to this extent due to the locality of such weather patterns. The plot shows however, that in this case the amount of precipitation is of the right order, and that the timing of the event is correct.

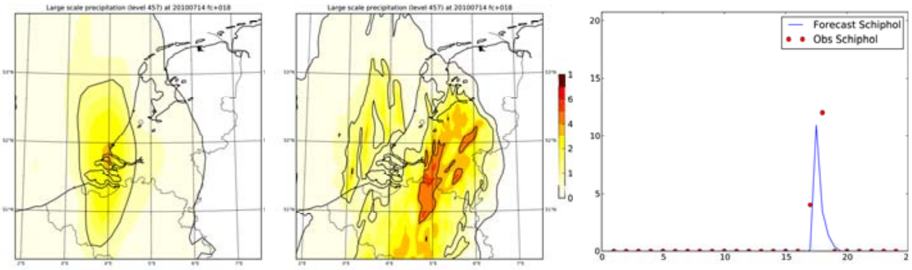


***Figure 4.5:** Forecasts of accumulated precipitation between 15:00 and 18:00 UTC, for HiRLAM (left), and for HARMONIE (middle) using a grid size of 400x400 points and HiRLAM boundaries. On the right a time series of the HARMONIE rain forecast for Schiphol (blue line) and observations (red dots) is presented.*

Wind

As mentioned in the description, a violent wind or (micro-) downburst passed over the east of the Netherlands, causing substantial damage. More detailed information on the exact nature of this phenomenon is given in [Groenland et al., 2010]. If we compare the wind speed as forecasted by HiRLAM and HARMONIE (cf. figure 4.6), we see that in HiRLAM relatively strong winds develop in large parts of the southeast, whereas in HARMONIE a small region of very intense wind occurs (wind speeds up to 100 km/h, gusts up to 140 km/h), associated with the band of most intense precipitation. This seems to accurately describe the events that took place near the town of Vethuizen (51°54’ N, 6°18’ E) that day. Also in the time series of the HARMONIE forecast (not presented here) we see that the order of magnitude of the wind is well represented.

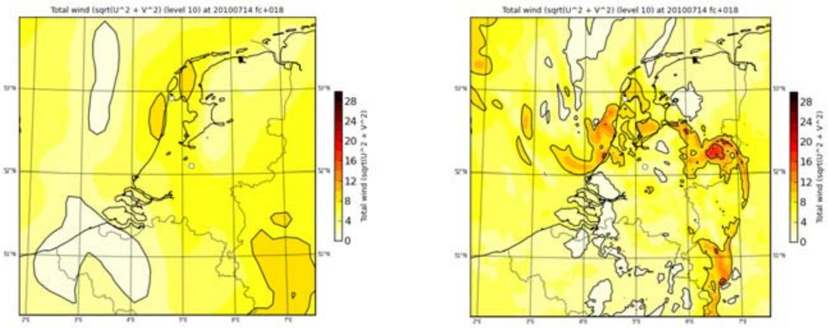


***Figure 4.6:** Wind speed at 10 m height above the surface for HiRLAM (left) and HARMONIE (right) at 18:00 UTC.*

In figure 4.7 the structure of the vertical wind is shown. The convergence zone that coincides with the area with the most intense precipitation is clearly visible as a border between the stable atmosphere in the northeast and the turbulent convective air mass in the southwest. The vertical wind speed along a vertical slice across the front gives an idea of the structure of the vertical wind. In the top row the front is just entering the slice from the right, showing a cell of air moving upward (in red) and already some downward motion at 600 hPa in front of the lifting cell. In the bottom row the structure responsible for the downburst is visible as an arc of convective cells from ground level at the right to around 250 hPa on the left. In dark blue we see the strong downward motion after the initial upward cell has passed.

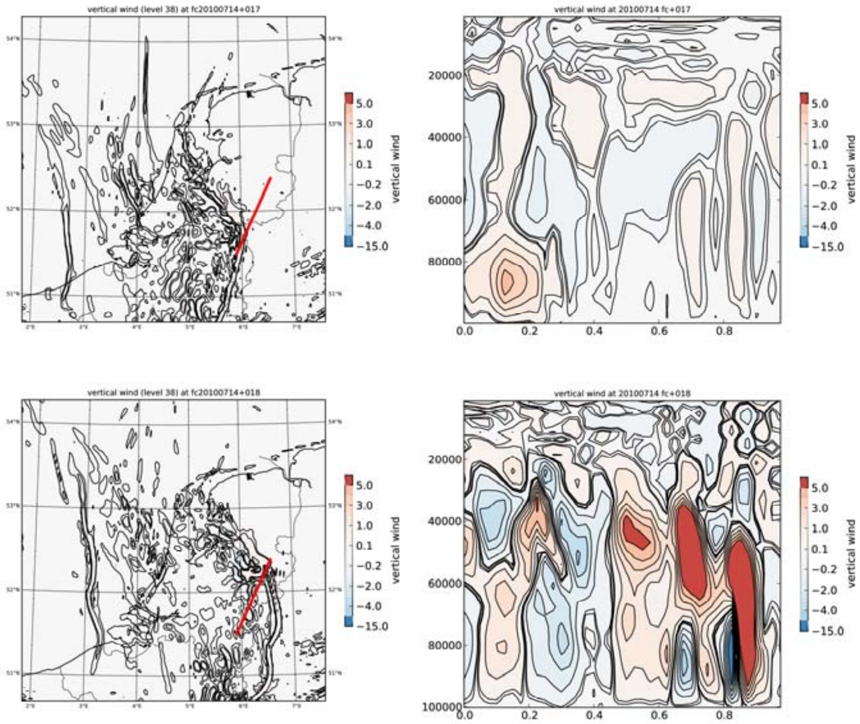


Figure 4.7: *The vertical wind speed at model level 38 (left) and along a vertical cross-section (right) marked by the red line, at 17:00 (top) and 18:00 (bottom) UTC. In the cross-sections, height is given in pressure (Pascal). The HARMONIE domain size used for the computations is 400x400 points.*

Convergence: domain size

In order to study the effect of the domain size on the forecast, the same simulation is executed on several different domain sizes: on the (default) 300x300 grid, where each grid box is 2.5 km, on a 400x400 and on a 500x500 grid, the latter effectively 1250 km times 1250 km. For all the HARMONIE simulations, the boundary conditions are retrieved from the HiRLAM model.

What happens in this case is illustrated in figure 4.9. In figure 4.8 we see the HiRLAM forecasts, in which the HARMONIE runs are embedded. Note that HiRLAM places the most intense rain west of the actual location of the front.

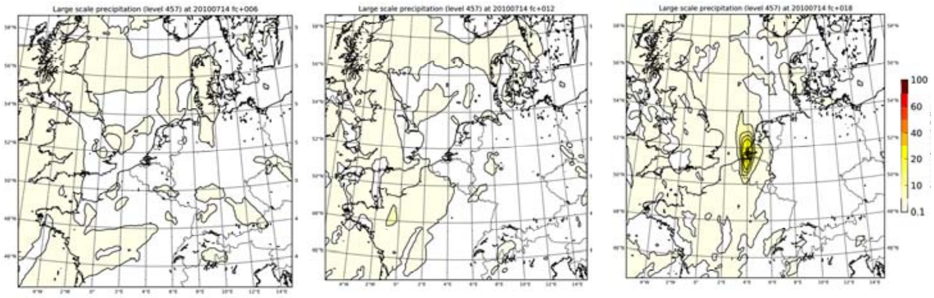


***Figure 4.8:** HiRLAM 3h accumulated precipitation forecasts, valid at 6:00 (left), 12:00 (middle) and 18:00 (right) UTC.*

In the HARMONIE run with 300x300 grid points (cf. figure 4.9, top right) we see that it has developed smaller scale structures with higher intensity rain more inland. The band of intense rain is captured well, but compared to the radar image (figure 4.9, top left) we see that the structure is lagging with respect to the observations. With both 400x400 and 500x500 grid points the location of the rain band is much better: farther east, and slightly tilted to the north.

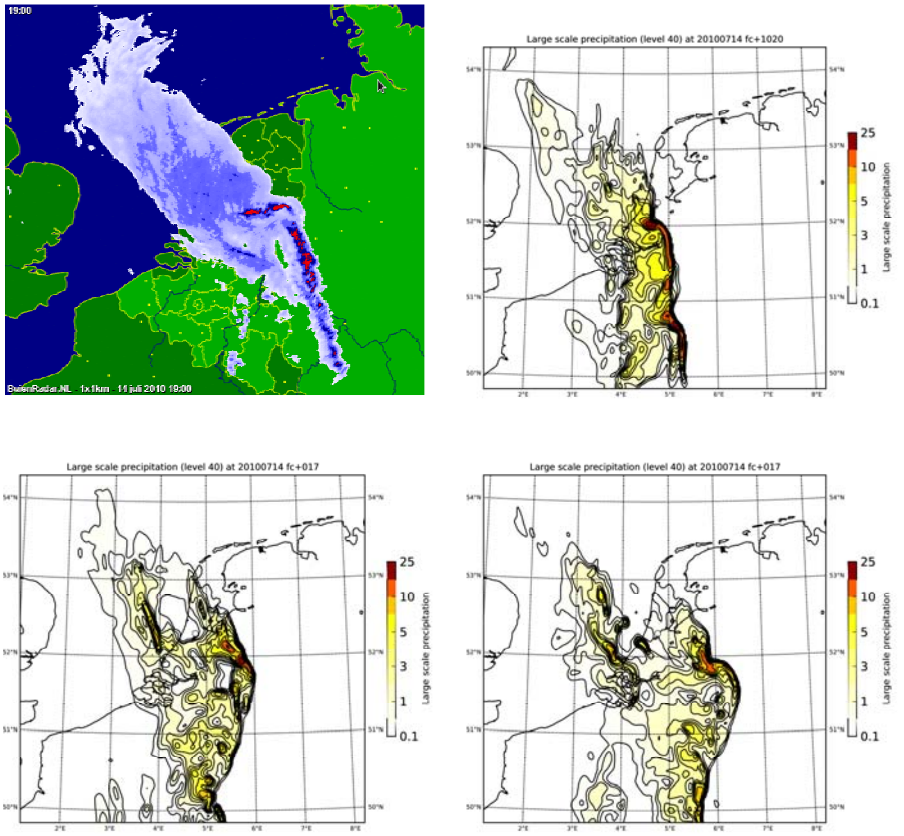


***Figure 4.9:** Precipitation intensity at 17:00 UTC. Presented is the instantaneous radar image (top left), and the precipitation forecasts from HARMONIE simulated on a domain size of 300x300 (top right), 400x400 (bottom left) and 500x500 (bottom right) points.*

The HARMONIE model receives its information of the area outside its own computational domain from its host model that provides the boundary conditions. For the majority of cases that we have studied the HiRLAM model was used as host. What we learned from our simulations, especially for convective events, is that HARMONIE in general appears to be unable to deviate substantially from the HiRLAM solution when the domain size is too small. For larger domains, like the ones with 400x400 or 500x500 grid points, HARMONIE is clearly able to produce its own dynamics, leading to a forecast that resembles the observations more closely. This means that to be able to run a high-resolution model like HARMONIE with confidence, producing reliable results, and adding value to the output of existing models like HiRLAM, it is important to use a larger domain size than the default setup. In practise an area of at least 1000 km by 1000 km is necessary to capture the developing systems, and preferably a somewhat larger domain should be considered to account for the different directions from which weather systems may approach. This, however, will also lead to an increased computational load, which is an important issue when using the HARMONIE model in an operational environment or running the model over longer periods of time such as months or years.

4.5 Case 3: Increasing the sea-surface temperatures, August 13, 2010

To be able to anticipate future weather, we have assessed for several weather events how they would evolve for changes in the sea-surface temperature (SST). The reason is that this will be one of the major vectors along which the influence of a changing climate will be transferred to local weather in the Netherlands. The local effects of global warming will generally be hard to predict, though modelling efforts with relatively high resolution climate models are under way. One effect that is probable and systematically present in most scenarios is a rise in the sea-surface temperature. In HARMONIE we can artificially increase the SST by any amount, and perform sensitivity studies with respect to precipitation and (transient) wind. The effects of an increased SST are most easily visible in weather phenomena that involve weather systems that approach from the west, overseas, and that have enough time to exert its influence. For example, the synoptic storm of January 18th, 2007 (cf. table 4.1) passes too quickly to show a notable influence of the increased SST, and the front that passed on July 14th in the summer of 2010, approached mainly from the south, over the landmasses of France and Belgium.

Description

In the late summer of 2010, a low-pressure system approaches the Netherlands over the North Sea, advecting disturbances from the west. In the morning of August 13, 2010, relatively cold air is pushed over the Dutch coastline, which instantly triggers rain along the coastal region. The low-pressure system advects a mass of relatively cold air over the warmer continent. At roughly 10.00 UTC a region of convergence along the coast develops into organized convection through lifting, triggering lightning and intense rain. The lifted-air dries out, and the showers disperse and disappear inland. Also, a second line of precipitation ± 30 km west is observed. This may be either due to the fact that a region in the middle of the English Channel/North Sea is normally warmer than its surroundings, leading to localized convection, or due to the outflow of the showers generated over land, generating secondary convection. This is a good example of how the coastal region is affected by a relatively warm sea. High relative humidity results from a period of large evaporation over sea and the land-sea transition subsequently triggers or forces convection, leading to heavy showers and thunderstorms until roughly 50 km inland.

Precipitation

If we compare the HARMONIE (domain size 400x400 grid points) forecasts to the precipitation radar (cf. figure 4.10), we notice that the qualitative features of the rain band are present in the HARMONIE forecast. The triggering along the coast line that is visible in the radar images is not reproduced by HARMONIE, but instead the rain band develops some 10 to 20 km inland, and hence rapidly evolves into the large stretched band as was observed with the radar. The second band over sea may have been too thin to represent properly with the HARMONIE 2.5 km grid. Another possibility is that it is caused by a well-known SST anomaly in the North Sea. If we compare the HARMONIE precipitation forecast to the HiRLAM forecast (cf. figure 4.11) we also see that HARMONIE improves upon HiRLAM rather well.

When we evaluate the vertical and horizontal winds, as well as the temperatures, as computed by HARMONIE (not shown here), we see how the incoming trough generates a thin band of large vertical velocity, extending quite high in the atmosphere, coinciding with the rain band. We also see how this region, roughly where Schiphol airport is located, is also subjected to a strongly variable horizontal wind, which changes direction several times, up to the 300 hPa level. Furthermore, HARMONIE produces graupel, a mixture of super cooled droplets and soft hail, whose amount is an indicator for the lightning intensity.

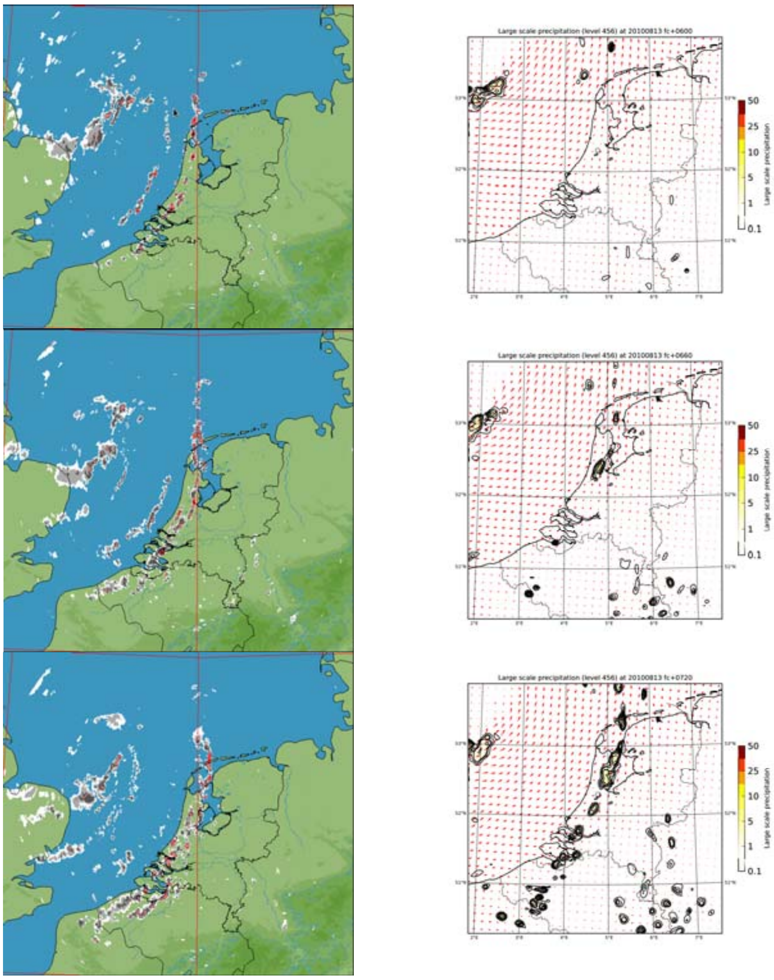


Figure 4.10: *Radar images (left) and HARMONIE forecasts of instantaneous precipitation at ground level (right) at 10:00 (top), 11:00 (middle) and 12:00 (bottom) UTC.*

If we compare the HiRLAM forecast to the HARMONIE forecast as shown in figure 4.11, we see differences in both the timing and the intensity of the precipitation. The HiRLAM forecast does not represent the sharp onset of the rain band very well, probably due to the fact that the rain band is not associated with a front, but is merely generated through lifting of slightly unstable air, triggering its highly convective nature. The all but complete absence of rain in HiRLAM, e.g. in the accumulation of 9.00 - 12.00 hour however is quite severe.

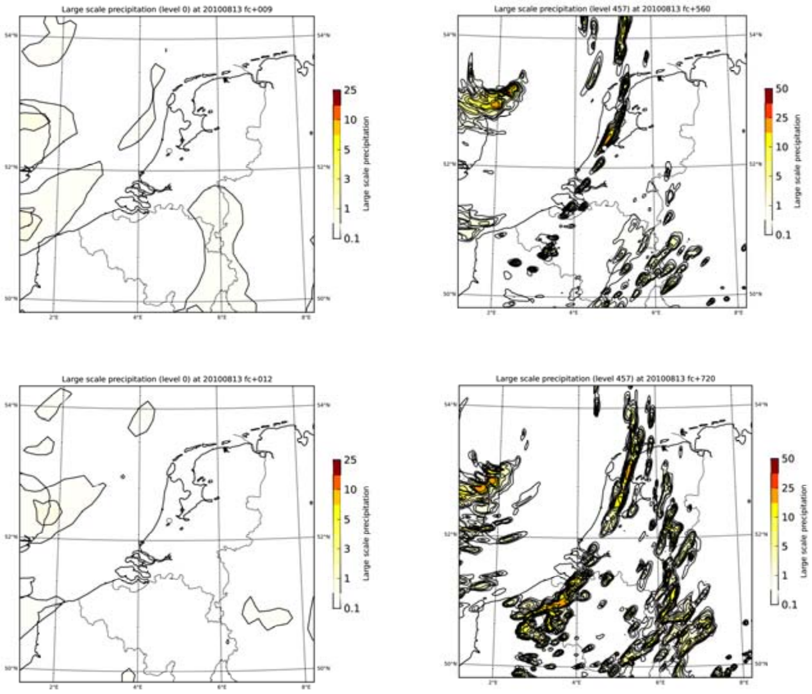


Figure 4.11: *Accumulated precipitation (3h) of HiRLAM (left) and HARMONIE (right) at 09:00 (top) and 12:00 (bottom) UTC.*

Influence of a modified sea-surface temperature

The low-pressure system, which for this case causes the convective rain showers in the coastal region, approaches from the northwest over a long distance over a relatively warm sea. As a result the sea-surface has enough time to exert its influence on the developing convective showers. For this reason this case is also very suitable for studying the effect of an increased SST upon the development of the convective showers.

In order to study the effect of a modified sea-surface temperature upon the convection, we artificially increased the temperature of the sea by 2 °C in every grid box of the HARMONIE model. The results of the increased SST run are presented in figures 4.12 and 4.13. In figure 4.12 the structure of the vertical wind is shown. The increased SST values clearly lead to stronger vertical model winds, both updrafts and downdrafts, at the frontal interface. The increased SST also leads to changes in the precipitation patterns and intensities, as can be seen from figure 4.13. Due to the higher sea-surface temperature convection is triggered more easily (closer to the coast), and more regions with deep convection and heavy precipitation along the coast and over the Yssel Lake develop.

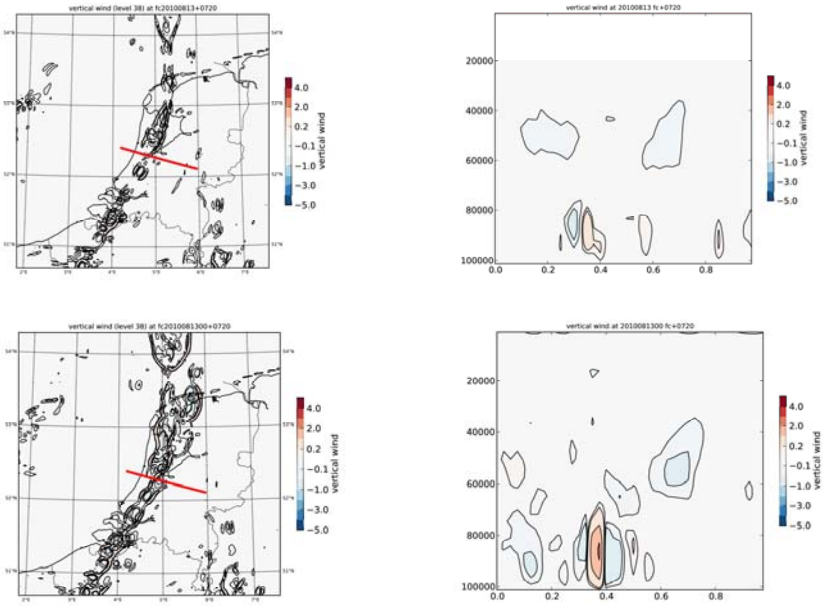


Figure 4.12: *Vertical wind speed at model level 38 at 12:00 UTC (left) and along a vertical cross-section marked by the red line (right). In the cross-sections, height is given in pressure (Pascal). The top row presents the HARMONIE results for the unperturbed case, the bottom row for the case with SST increased by 2 °C.*

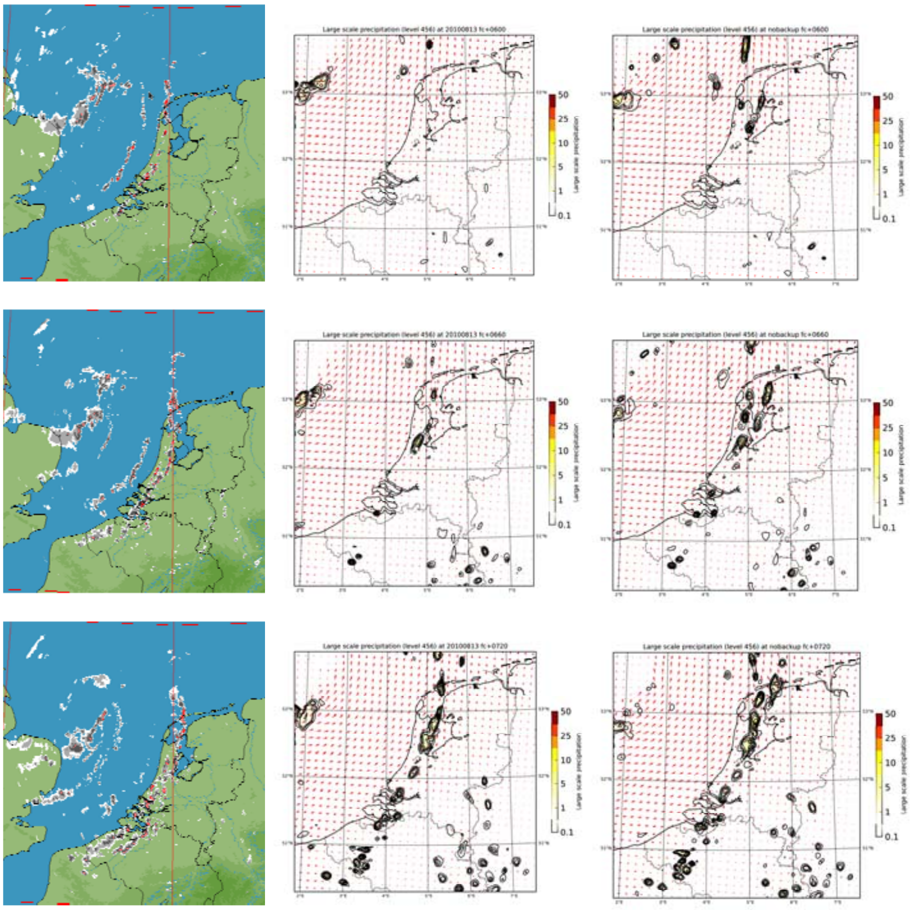


Figure 4.13: *Radar images (left) and HARMONIE forecasts (in the middle the unperturbed run and right the run with SST increased by 2 °C) of instantaneous precipitation at ground level at 10:00 (top), 11:00 (middle) and 12:00 (right) UTC.*

4.6 Case 4: Stratocumulus cloud deck, January 30 – February 1, 2011

Stratocumulus clouds are only a few hundreds of meters thick. Despite their relative shallowness, they reflect back to space more than 50% of the down welling solar radiation, and can cause a poor visibility if their cloud base is very close to the ground surface. In addition, in the wintertime period stratocumulus clouds may produce freezing rain.

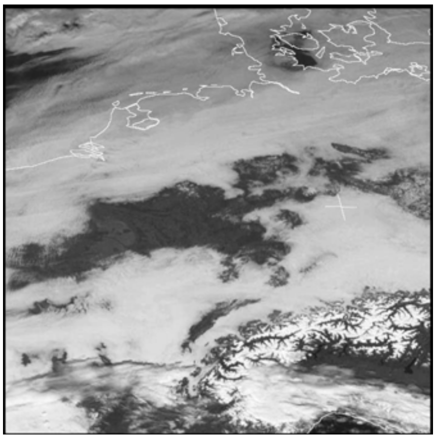


Figure 4.14: *A persistent stratocumulus cloud deck covering the Netherlands. Satellite image is from 31 January 2011, 12h UTC.*

Description

The satellite image of 31 January 2011 12 UTC shows a horizontally extended stratocumulus cloud deck covering the Netherlands (cf. figure 4.14). As the condensed water amount in low clouds is typically very small, on the order of 0.1 g/kg, it is notoriously difficult for weather and climate models to capture these clouds well. In practice this means that if the total water specific humidity is only 0.1 g/kg off, or the temperature just a few tenths of a degree Celsius too high, an unsaturated, clear atmosphere will be predicted [De Roode, 2007]. Indeed, the amount of stratocumulus and persistence of the observed stratocumulus cloud deck is underpredicted in various European weather forecast models, such as the ECMWF, COSMO, and HiRLAM model. Also in HARMONIE the stratocumulus cloud deck disappears for a couple of hours around noontime (cf. figure 4.15). A preliminary analysis of the boundary layer humidity indicates that it is a bit too low during the clear air period.

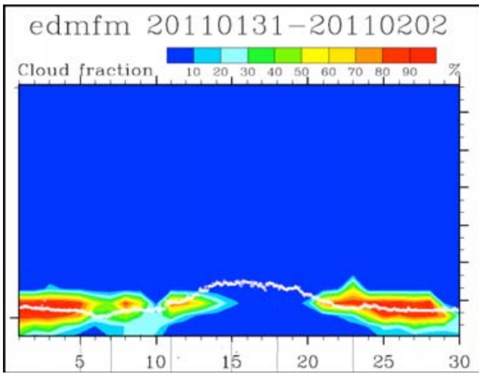


Figure 4.15: *Time series of stratocumulus clouds forecasted by HARMONIE for the Cabauw site. Presented is the cloud fraction, ranging from 0% to 100%, as computed by the new model cloud scheme EDMF. The white line represents the observed cloud base height derived from the Cabauw measurements.*

A couple of possible reasons for the underestimation of stratus in the winter period have been suggested. In general an accurate initialisation of the model is vital for the quality of the weather prediction. For example, if the lower atmosphere is initialised too warm or too dry, the cloudiness will be too low. In the extreme case that no clouds are initialised at all, the process of radiative cooling at the top of the cloud layer will not occur, thereby leading to a persistent warm bias and a lack of low cloud fields. This situation is not unlikely, as errors of the order of a few tenths of a degree in the temperature can be sufficient to yield a clear atmosphere. Other reasons that have been put forward are errors in the surface fluxes of heat and moisture, or excessive entrainment of dry air present just above the cloud top. To verify these hypotheses, HARMONIE model results are compared to observations from the Cabauw measurement site and to numerical experiments done with a large-eddy simulation (LES) model. The advantage of the LES model is that due to its extreme high-resolution (typically 10 – 100 m), the model is capable to resolve most of the small-scale features. As such LES models are considered as the most appropriate tools to obtain a better understanding of low clouds and provide a suitable means to test hypotheses.

Results of testing our hypotheses

It was found that the LES model is well capable of predicting a solid and persistent cloud deck. Figure 4.16 shows the evolution of the cloud base and cloud top heights. The modelled cloud base height is close to the observations. The cloud top height is about 600 m at 12 UTC, which is in agreement with the radiosonde observations. During the full period of the simulation the cloud layer is thick enough to prohibit the development of clear air patches. This is in contrast with the HARMONIE result, which shows the disappearance of the clouds at 16 UTC (see figure 4.15). According to our observations at that time the cloud layer has a depth of approximately 200 m.

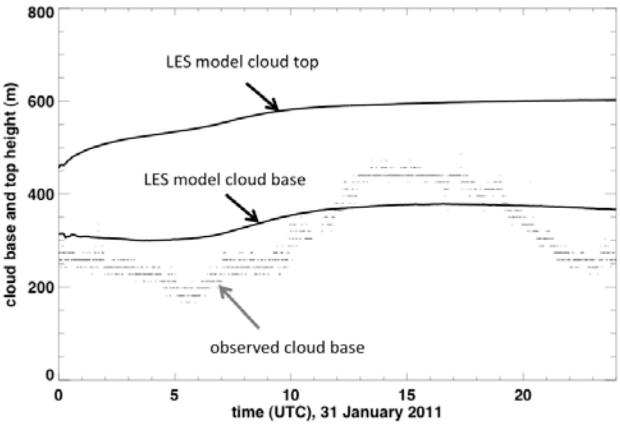


Figure 4.16: *Observed lowest cloud base height (dots) at Cabauw, 31 January 2001, and the cloud base and top heights simulated by the LES model (solid lines).*

In the cloud layer the vertical resolution of the HARMONIE model is about 70 m, which means that the cloud layer may only be present at two model levels and be diagnosed as a cloud layer of just 140 m thick. If the cloud layer depth is significantly underestimated, the amount of radiative cooling will also be smaller.

Some additional experiments were performed to assess the effect of errors in the surface fluxes and to question whether an initially clear atmosphere will fill up with low clouds during the day. It was found that when the LES model was initialised with a cloud free atmosphere, in the simulation only a few patches of thin clouds were found. Because there were no clouds present from the start, the cloud radiative cooling process was not activated. As cloud formation is more likely in colder air, the lack of radiative cooling hinders the formation of a solid stratus layer simply because the air is too warm to allow condensation. Furthermore, it was found that when the surface fluxes were set to zero or doubled with respect to the reference case, the cloud layer did not break up. In other words, for this stratus case an error in the calculated surface fluxes is not a likely candidate to explain a poor prediction for the cloudiness.

Conclusions

On 31 January 2011 the HARMONIE model predicted a period with fog and a clear atmosphere whereas the observations showed a persistent stratus layer with a cloud base above 200 m. A numerical experiment with a high resolution LES model was carried out to demonstrate that such a model is well capable of predicting the stratocumulus cloud layer. Further sensitivity tests showed that the precise magnitudes of the surface heat and moisture fluxes couldn’t explain an erroneous break of the cloud. The heat and moisture budgets are in approximate balance for this case and variations in their magnitude play a minor role in modifying the cloud layer depth.

The observations show that the cloud layer during some periods becomes smaller than 200 m. The vertical configuration of the grid layers in the HARMONIE model is rather coarse such that the cloud layer may only be present at 1 or 2 model layers, which makes its representation much more sensitive to small errors in the thermodynamic state of the atmosphere. Specifically, errors of the order of 0.1 °C in temperature may already make the difference between a clear atmosphere and one that is filled with low clouds. Therefore, predictions of meteorological conditions that favour the formation of low cloud will likely benefit from a finer vertical resolution.

If LES models are so well capable of reproducing low clouds, one may wonder why they are not used for weather predictions? The fact that these models use such a fine resolution makes them computationally expensive. However, some preliminary studies are currently performed with the Dutch LES model running on a Graphical Processor Unit (GPU) [Schalkwijk et al., 2012]. The benefit of such an approach is a detailed prediction of the weather, though at a rather limited horizontal domain size. If the area of interest is small, like the Schiphol area, such an approach might be promising for a better prediction of stratus clouds.

Although the stratocumulus cloud deck does not persist in the HARMONIE results in contrast to the observations, various other tests with EDMF / EDKF parameterization scheme show promising results with regard to the representation of low clouds.

4.7 Case 5: The Urban Heat Island effect, July 20, 2010

Urban Heat Island effect

The Urban Heat Island effect may present an increasing health risk to citizens in a warming climate unless adaptations are taken that diversify the cityscape by the introduction of green and water. To analyze such measures engineering models need realistic forcings from weather models at the scale of a city and its surroundings.

In this case the results of a preliminary study into the Urban Heat Island effect of Rotterdam are presented [Ben Wichers Schreur and Sander Tijm, 2010]. It is an example of applying HARMONIE at a resolution of 500 meter and studying the effect of a detailed description of the surface conditions. For this purpose the HARMONIE system contains a Town Energy Budget (TEB) module that models the effect of the built environment and the heterogeneity of the landscape on local weather forecasts. The quality of high-resolution weather prediction models like HARMONIE and its sensitivities to the resolution and accuracy of the description of the surface conditions may be assessed in the current climate.

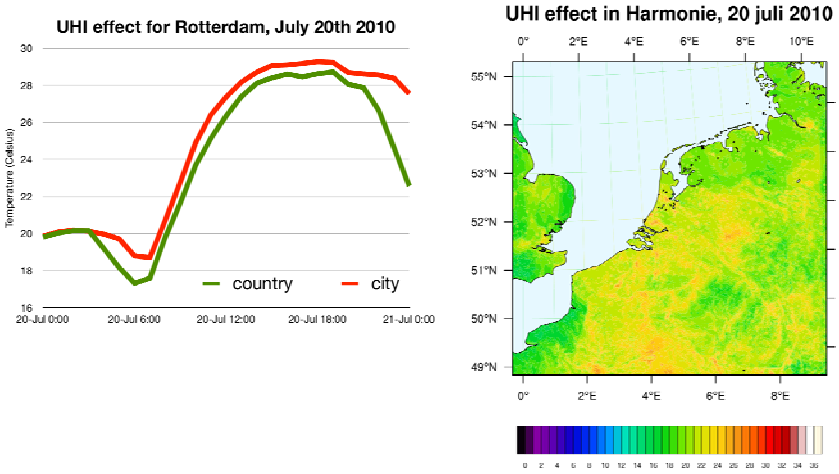


Figure 4.17: *Observed temperature time series in Rotterdam (left) and HARMONIE screen level temperatures (red is hot, green is cool) for 21:00 UTC on the 20th of July 2010 (right).*

Description

July 20th was the last warm day of the summer of 2010 in the Netherlands. For this day a 24 hour forecast was made with HARMONIE, version 36h1, at a resolution of 500 meters on a 1000x1000 grid. The metropolitan areas release their heat more slowly than the surrounding countryside. In figure 4.17 these areas can be identified by their red colour. For the Rotterdam Rijnmond region this slow cooling amounts to 5 degrees Celsius.

Surface specification

The American Weather Research and Forecasting Model WRF [Skamarock et al., 2005] uses a comparable town energy budget model. It offers greater flexibility in the specification of surface conditions and the use of alternative data sets. The UHI case study was repeated with WRF using two different land-use classifications, one given by the US Geological Survey and the other derived from MODIS satellite data. The resulting temperature distributions, given in figure 4.18, show that the modelled UHI effect depends strongly on the land classification used and the resolution of the underlying data set. The interdependence of the surface modelling and the available data sets makes model calibration a challenge.

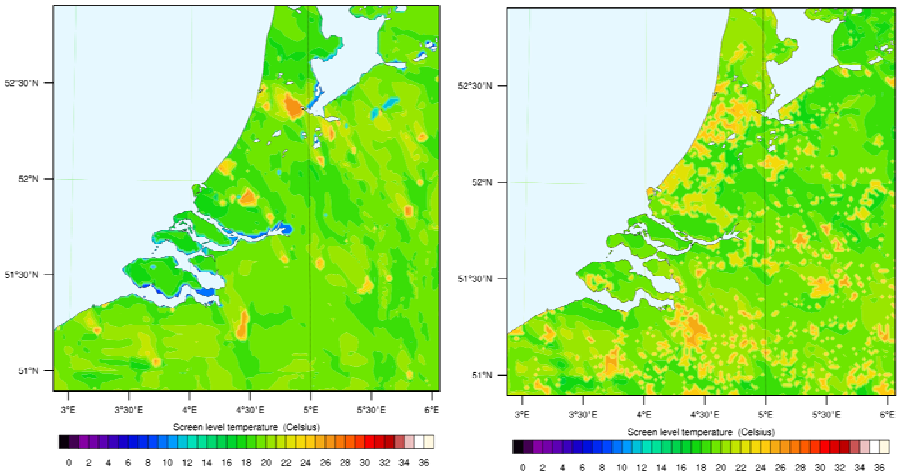


Figure 4.18: *WRF screen level temperatures for 21:00 UTC on the 20th of July 2010 (left using the USGS and right using the MODIS land classification scheme).*

Conclusion

State of the art high-resolution numerical weather predictions models are able to model the Urban Heat Island effect by using town energy budget models. An accurate prediction of this effect requires not only a calibration of the city effect modelling, but also a thorough evaluation of the land-use classification data used. This will also be of importance to the modelling of other weather events affected by surface heterogeneity, e.g. convective rainfall.

4.8 Conclusions

It is shown that the next generation non-hydrostatic weather prediction model HARMONIE, operating at a very fine horizontal spatial grid resolution (1~2 km) and explicitly resolving vertical convective motions, more realistically captures deep convective events as compared to the current operational model HiRLAM. In general strong winds and heavy precipitation, associated with convective events, are predicted rather well. The higher model resolution also results in a more detailed picture of the wind. In general, HARMONIE can represent small regions with very high wind speed, which are mostly absent in HiRLAM. Furthermore, HARMONIE is capable to compute the structure of the vertical wind, whereas in HiRLAM the vertical velocity is not computed explicitly. This is an important difference between the two models, as the structure of the vertical velocity often reveals the development of extreme wind events such as downbursts. Important types of these events are the so-called cold pools. Cold pools develop if rain evaporates which leads to a subsequent cooling and sinking of cold air. If there is a lot of evaporation of rain, this can eventually trigger intense downdrafts, which can reach the ground and cause a lot of damage. Various model runs with different horizontal grid resolutions have shown that

HARMONIE can resolve the dynamical structure of cold pools, including the corresponding averaged rainfall amounts, provided that the horizontal resolution of the model is finer than 2.5 km.

If we compare the current operational weather prediction model HiRLAM with HARMONIE, we observe that in cases where HiRLAM performs well, such as large synoptic scale storms, HARMONIE gives similar results, but at a higher resolution and with more detail.

HARMONIE contains various types of hydrometeors, such as rain, graupel and snow, as prognostic variables. Also hail is in the model but its output is not yet available. Being part of the model formulation, less post-processing is necessary to assess a situation with possible wintery precipitation. This approach is very different from HiRLAM, where all precipitation is treated as liquid water and should be post-processed, using the atmospheric vertical temperature profile, to a precipitation type, such as (wet) snow or (freezing) rain, that is most probable reaching the ground. The hydrometeors in HARMONIE are calculated as a three-dimensional field, available at each model level or altitude.

In general, also low clouds are better captured within HARMONIE. Low clouds, such as e.g. stratocumulus clouds, are very important for aviation. Despite their relative shallowness (they are only a few hundreds of meters thick) they can cause poor visibility if their cloud base is very close to the ground. As the condensed water amount in these clouds is typically very small, it is notoriously difficult for weather prediction models to predict these clouds well. Indeed, the amount of stratocumulus clouds and the persistence of observed stratocumulus clouds are underpredicted in various European weather prediction models, like ECMWF and COSMO. But, various other tests with the new physical cloud scheme EDMF/EDKF [Siebesma et al., 2007] in HARMONIE have shown promising results with regard to the representation of low clouds.

Compared to HiRLAM, HARMONIE seems better capable to predict the dynamical structure of fog fields and of extremes in cloud water at the lowest model levels. Nevertheless, several case studies of radiation fog events have revealed that HARMONIE, among other models, has difficulties in forecasting both the precise onset and the development of the fog layer. For fog forecasting, a high vertical resolution in the lowest few hundred meters of the model appears to be of great importance. Past research has also shown that [Tardif, 2007]. A lower vertical resolution leads in general to a delay in the onset. The vertical resolution seems to be even more important than the use of a more sophisticated radiation scheme. Broadband schemes, which are computationally inexpensive, are suitable as well, provided that they are frequently called upon during the time integration of the model equations [Tudor, 2010]. Overall, our case studies have shown that the HARMONIE model setup with the finest resolution near the surface, i.e. 4 layers in the lowest 100 m, performs better than the more coarse setup which has only 2 layers in the lowest 100 m.

For several case studies it has been shown that HARMONIE predicts well the general shape of rainfall patterns. Though the rainfall pattern is predicted fairly well, the rainfall intensity and the location of the onset of the precipitation seem to be highly sensitive to the size of the computational model domain. For smaller model domains the onset of the precipitation is often too early and the intensity is too low. Fortunately, the model output converges when the domain size is increased. On the other hand, the size of the computational model domain should be limited to reduce the computational load. To be able to run the high-resolution model HARMONIE with confidence, producing reliable results with acceptable computational load, a domain size of 400x400 grid points, using the standard horizontal resolution of 2.5 km, is recommended during the forecast, to ensure the development of the convective structures such as storms, squall lines, etc. This size ensures the autonomous development of the dynamics of convective systems, making sure that the HARMONIE forecast not only adds smaller scale information to HiRLAM, but that it can really employ the advantages of a non-hydrostatic model to yield a state-of-the-art forecast.

State of the art high-resolution weather prediction models, such as HARMONIE, are able to model the Urban Heat Island effect by using a town energy budget model. An accurate prediction of this effect, however, requires not only a calibration of the city effect modelling, but also a thorough evaluation of the land use classification data that is used. This will also be of importance to the modelling of other weather events that are affected by surface heterogeneity.

The impact of increased sea surface temperature (SST) on rainfall amounts and winds has been studied. In HARMONIE it is easy to artificially increase the SST by any amount. Several case studies have shown that the effect of an increased SST is most easily noticeable for weather systems that approach from the west, i.e. overseas, and that have enough time to exert its influence. Weather systems that pass from other directions or that pass to fast, hardly show any influence from the increased SST. According to the performed case studies, it seems that the main effect of an increased SST is that for weather systems that approach from the sea, convection close to the coastal line is triggered more easily, rainfall patterns change and coastal rainfall amounts and winds are more intense.

5 HARMONIE as a climate tool

5.1 Why and how using HARMONIE as a climate tool?

HARMONIE has been developed as a high-resolution numerical weather prediction tool. It is a limited area model that needs lateral boundary conditions provided by a host model such as HiRLAM or ECMWF. A typical model domain size for HARMONIE is 1000 x 1000 km^2. In case of a horizontal wind with velocity 10 m/s, this means that any property is transported through the model domain on a time scale of 1~2 days. Beyond this timescale the importance of the lateral boundary conditions is increasing rapidly at the expense of the initial conditions of the model. As a result, numerical weather predictions on this limited model domain beyond a time scale of 1~2 days are dominated by the boundary conditions and the initial conditions do little contribute to that. An important question that than arises is: How and why can we use HARMONIE as a climate tool beyond time scales of the order of a few days?

For time scales beyond one or two days the outcome of a model run will be more and more dependent on the lateral boundary conditions. If these boundary conditions are provided by a global climate model, it will then act like a looking glass: HARMONIE will resolve the atmospheric processes with more detail. But obviously the realism of the HARMONIE model will be dependent on the realism of the climate model in which it is in embedded. This technique that has been applied already with hydrostatic limited area models at coarser resolutions of 10~25 km, such as the regional atmospheric climate model RACMO, goes under the name of *dynamical downscaling* and has been proven a successful concept for designing regional climate scenario's.

The goal here is to evaluate HARMONIE for its skill for predicting precipitation in both a climate and a weather prediction mode. To this purpose we will evaluate the August 2006 period during which a record amount of precipitation was recorded. We will compare the results with RACMO which is presently the regional climate model used at KNMI. RACMO however is a hydrostatic model that runs typically at a coarser resolution of 10~20 km while HARMONIE will run at a much higher resolution of 2.5 km.

5.2 Motivation and background for the August 2006 case

Future climate scenarios as anticipated by Global Climate Models (GCM's) predict a decrease in summer precipitation in the Southern part of Europe and an increase in the Northern part. The Netherlands is in between these 2 regions and therefore the change in mean summer precipitation is relatively uncertain. Despite the increase of average temperature over the last 60 years over the Netherlands, there is no systematic increase of the observed precipitation over late summer. Figure 5.1 shows the time series of the 20-year moving average of the mean precipitation for late summer (July, August, September) in the Netherlands. Large decadal variations related to variations in the large scale atmospheric circulation can be observed, but no significant trend in mean summer precipitation is present. A significant trend in the growth of difference between inland and coastal precipitation however can be observed (see figure 5.1); the difference between coastal and inland precipitation was rather small in the 1950's but has increased to a significant difference in more recent years. In Lenderink et al. (2008) (hereafter referred to as L08) it is argued that this difference is related to the change of the sea surface temperature (SST) of the North Sea, which has increased by 1.2-1.5 K for the late summer over the period considered. Indeed, higher SST's leads to a moister atmosphere over the North Sea and supports an increased precipitation over land in summer, provided that the North Sea is in the upwind direction. This hypothesis has been tested by L08 for the August 2006 period. August 2006 was an exceptionally wet month in the Netherlands, in particular near the coast where amounts exceeded 300% of the climatological mean. August 2006 was preceded by an extremely warm July with a monthly mean temperature of almost 1K higher than recorded in any other summer month in the period 1901-2006. This had resulted in exceptionally high SST's in the North Sea by the end of July. Since August 2006 was characterized by a northwesterly circulation, it is an excellent case for studying the effect of anomalous high North Sea SST's on the precipitation in the Netherlands. Through a comparison of short-term numerical integrations with the regional climate model (RACMO) fed with the observed high SST's and additional numerical integrations in which RACMO was fed with lower climatological SST's it was demonstrated in L08 that the extreme precipitation in especially the coastal regions could be related to the high SST's over the North Sea.

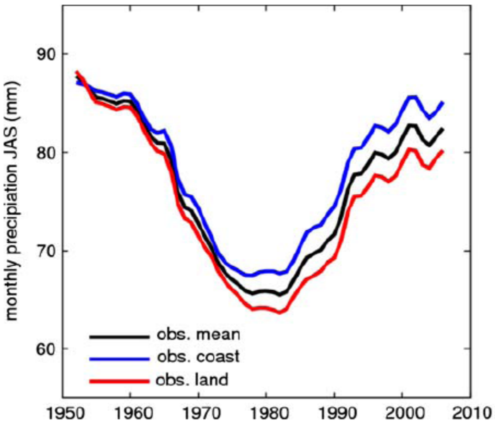


Figure 5.1: *Time series of the 20-year moving average of mean, coastal and inland precipitation for late summer (July, August, September) in the Netherlands.*

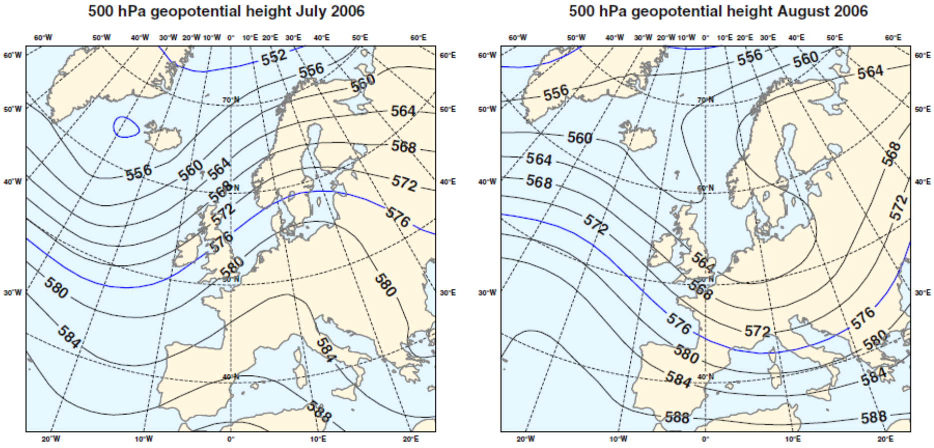
Although RACMO was capable of reproducing reasonably well the anomalous high observed precipitation in the coastal region there were also some systematic differences with the observed precipitation. Whereas the observations indicate that the maximum of the monthly mean precipitation occurred around 30 km inland from the coast, the modelled precipitation of RACMO predicted a maximum exactly at the coast. It was hypothesised that this mismatch might be due to the hydrostatic formulation of the model. This implies that the updrafts of the convective precipitating cumulus clouds are not explicitly calculated by the model dynamics but instead diagnosed by a relatively simple statistical description in RACMO, a so called parameterization. As a result hydrostatic models might have problems of transporting the convective precipitating systems further inland, which might result in precipitation patterns that are too much shifted toward the coast. HARMONIE, on the other hand, is a high-resolution atmospheric model that has a non-hydrostatic formulation. That implies that the cumulus convective updrafts that create the precipitation are explicitly resolved by the model and can be advected inland by the model. So, one motivation of this study is whether HARMONIE is better capable of positioning the peak of monthly precipitation mean at the observed position. This is only one of the many motivations to evaluate HARMONIE for the August 2006 period.

High-resolution non-hydrostatic atmospheric models such as HARMONIE form a new generation of numerical weather prediction (NWP) models that due to the ever-increasing computational resources are now at the verge of getting operational in many meteorological services all over the world. This new type of mesoscale models are promising since they operate at a resolution in the range of 1 to 5 km and are therefore capable of partially resolving convective precipitating systems such as observed during August 2006. They are also problematic at the same time because they only *partially* resolve these precipitating systems and therefore partially require parameterization for the unresolved part of the precipitating systems. How to treat cumulus convection in mesoscale models that operate in the so-called *Grey Zone* is an active field of research and for HARMONIE a pragmatic choice has been made. It is assumed that cumulus convection that exceeds a vertical extend of 3 km is resolved while shallower cumulus convection is still parameterized. Although this new generation of models are promising, evaluation studies with these types of models operating in the grey zone indicate they tend to overpredict precipitation.

It is for this reason that we explore in this study a comprehensive evaluation of the capability of HARMONIE of reproducing the extreme precipitation amounts such as observed in August 2006. To this purpose we will evaluate HARMONIE in two settings. First we will run it as a concatenation of 36hr forecasts where we will use for each forecast the last 24 hours for all days of August 2006. Secondly we will run HARMONIE in a so called climate mode which means that we initialise the model at July 31 2006 and make a single run for the whole month of August 2006 without reinitialising the model each day. In section 5.3 we will further describe the case setup and the synoptic conditions. In section 5.4 we will evaluate these HARMONIE experiments with observed SST's. In section 5.5 we will do sensitivity experiments where the SST's are artificially increased and decreased by 2K to explore the effects of the North Sea SST's on the precipitation over the Netherlands. In section 5.6 we repeat the same experiments as in section 5.4 but this time forced with a better and higher resolution prescribed SST such as observed by the NOAA satellite. These SST's are not used yet in the operational HARMONIE, so it is interesting to explore the potential added value for the forecasts of making operational forecasts with improved observed SST's. Finally, section 5.7 will contain a summary of the results and a further outlook on future developments.

5.3 Synoptic situation and case setup

July 2006 was extremely warm and dry in the Netherlands. During the last 2 days of July a change in weather regime took place whereby the very warm anticyclonic atmospheric circulation, that characterized most of July, was replaced by a cold cyclonic circulation. This northwesterly circulation (see figure 5.2) persisted during the whole month of August and gave rise to extreme precipitation in the Netherlands. In particular, the local precipitation amounts in the coastal zone less than 50 km from the coastline were exceptionally high. At some coastal stations precipitation totals were recorded up to five times the climatological average of August.



500 hPa geopotential height July 2006

500 hPa geopotential height August 2006

Figure 5.2: *Synoptic situation during July (left) and August (right). Shown is the 500 hPa height obtained from the operational ECMWF analysis.*

Various simulations with HARMONIE have been performed to assess the capability of HARMONIE to reproduce the precipitation in the August month and to further assess the influence of the SST on the precipitation. For all experiments a domain size is chosen of 750 x 750 km^2 and a horizontal grid spacing of 2.5 x 2.5 km^2. The model uses 40 vertical levels. Lateral boundaries and SST's are given by the operational ECMWF analyses and updated each 6-h and interpolated in time. The ECMWF analyses have a horizontal resolution of 0.25°.

HARMONIE is operated in two different modes: a hindcast mode and a climate mode. In the hindcast mode, consecutive simulations are started each day at 12 UTC from the ECMWF analysis. Each model integration is 36 hours long and the period from 12h to 36h is used for the evaluation. The hindcast mode enforces the simulated atmospheric circulation to stay close to the observed circulation, which facilitates a comparison with observations on a daily level. The hindcast results are therefore indicative for what we can expect from HARMONIE when used as an operational weather prediction model. Soil moisture is obtained from the ECMWF analysis and is re-initialised each 36-h model integration. This ideally prevents feedbacks through the soil moisture and therefore isolates the direct effect of SST on precipitation. In the climate mode, HARMONIE is initialised only once at July 31 running continuously until the end of August using the same ECMWF boundaries. These type of runs are more indicative how HARMONIE performs as a regional climate model, of course in this present case fed with the best optimal boundary conditions which is the

ECMWF analysis. In future climate runs, results will be more deteriorated due to imperfect lateral boundary conditions of a climate model. So the present climate runs give an indication of the performance of HARMONIE as a regional climate mode, *given* perfect boundary conditions.

Finally a few words on the used versions of HARMONIE: For the hindcast we used cycle 36.1.4, which is the most recent version. For the climate mode we have used cycle 36.1.3, which is a previous version since it was at the moment of writing not possible yet to run HARMONIE in the climate mode using the most recent version. However the differences for precipitation for those different versions are small, at least much smaller than the differences between using the model in a climate mode and a hindcast mode.

5.4 Results and evaluation of the HARMONIE simulations

Precipitation observations of approximately 320 stations in the Netherlands are used and its spatial distribution is shown in figure 5.3. In addition we also use rain radar results (see figure 5.5 bottom right) for the first three weeks of August (during the last week of August there were too many missing data from the radar observations). Near the coast and Lake Yssel the average monthly precipitation sum is 210 mm, with maxima near 300 mm at a few locations. Inland precipitation amounts are 150-180 mm on average. The rain radar data show in addition that precipitation rates over sea are substantially smaller than in the coastal region. The climatological average for the Netherlands (1971-2000) for august is 61 mm.

__Figure 5.3:__ August 2006 precipitation sums for the observational ground stations.

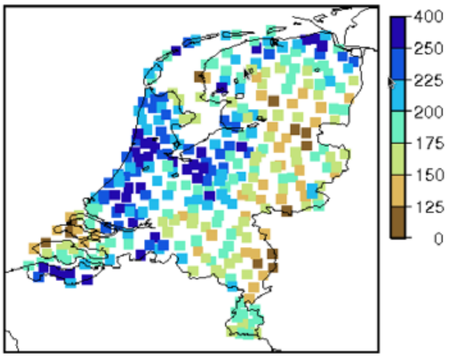


Table 5.1 and figure 5.4 show that both the climate and the hindcast simulations of HARMONIE overpredict the accumulated precipitation by around 15%. It is interesting to note that the predicted precipitation amounts of the HARMONIE climate runs are not deteriorated with respect to the hindcast, despite the fact that the climate simulation is only initialised once at the beginning of the month. The precipitation amounts simulated by RACMO stay closer to the observations and the final underprediction is mainly due to the last few days in August.

Table 5.1: Total precipitation amounts for various HARMONIE and RACMO experiments and for the ground (station) and radar observations. Accumulated values are given for the first 3 weeks of August 2006 and for the whole month.

	3 weeks	**August 2006**
Experiment	**Precipitation (mm)**	**Precipitation (mm)**
HARMONIE_HINDCAST	165	224
HARMONIE_CLIMATE	144	224
RACMO_HINDCAST	156	173
GROUND_OBS	135	194
RADAR_OBS	125	–

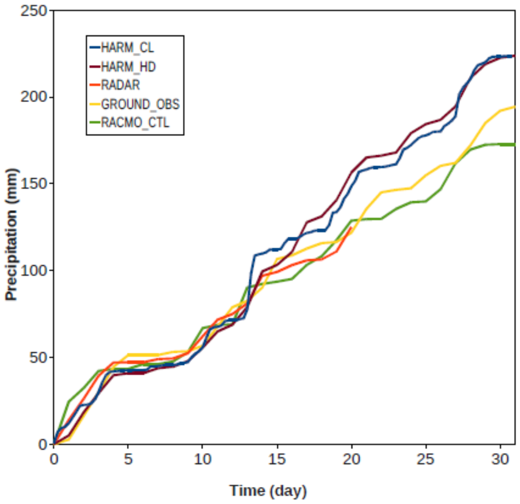


Figure 5.4: *Time series of the accumulated precipitation for August 2006 for the Netherlands of: HARMONIE Climate (blue), HARMONIE Hindcast (brown), RACMO Climate (green), ground observations (yellow) and radar observations (red).*

The spatial distribution as seen by the three simulations and by the rain radar for the first three weeks is displayed in figure 5.5. Though the overall qualitative picture of more precipitation in the coastal regions is visible in all simulations, also large differences can be observed. RACMO misses most of the local high precipitation amounts while the precise locations of the high precipitation amounts in HARMONIE are not at the observed locations.

To further quantify the coastal effects, we analyse the accumulated rainfall as a function of distance to the coastline. Since we want to compare the results also with the rain radar data we concentrate on the first three weeks of August. Different zones were defined based on the distance to the coastline (coastline includes the Lake Yssel). The precipitation rates (mm/month) for the different zones are shown in figure 5.6. Both ground and radar observations show a peak in the precipitation at around 20 km inland from the coast with a value around 230 mm/month. Further away from the coast these values decrease to values of around 160 mm/month, still much larger than the climatological values. All model simulations predict more precipitation near the coast than inland in agreement with the observations. Both HARMONIE simulations overestimate the inland precipitation. For the coastal region it is surprisingly enough the HARMONIE hindcast that strongly overestimates the precipitation amounts. RACMO simulates overall the correct precipitation rates but the peak value is exactly at the coast in disagreement with the observations. As anticipated in the introduction this might be the result that all convective processes in RACMO are parameterized in a diagnostic manner so that there is no mechanism to transport the convective systems more inland.

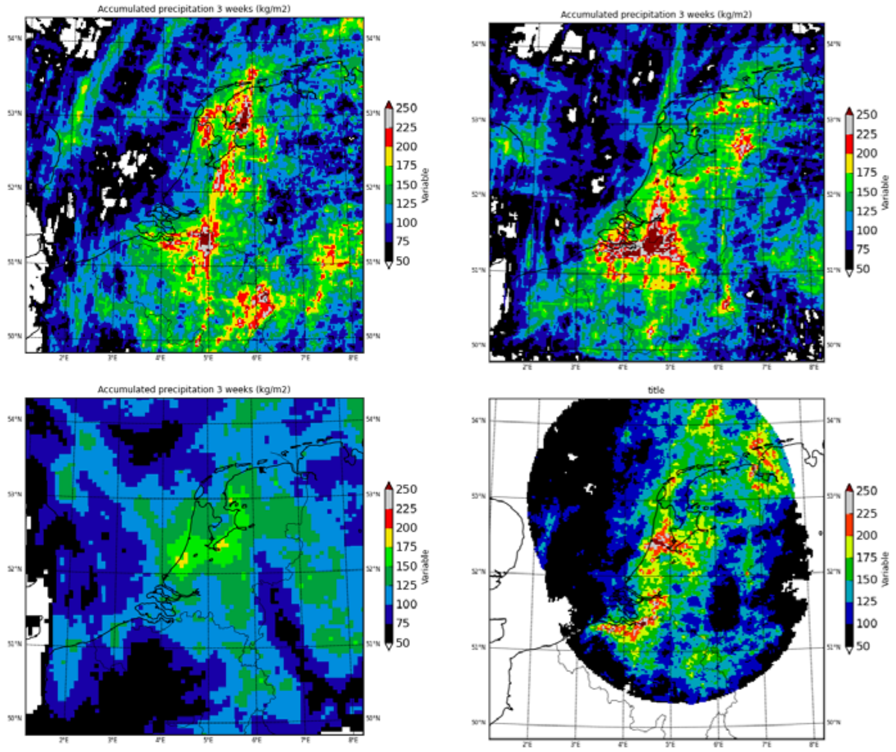


Figure 5.5: *Integrated precipitation for the first three weeks of August 2006 for: HARMONIE Hindcast (top left), HARMONIE Climate (top right), RACMO Climate (bottom left) and radar observations (bottom right).*

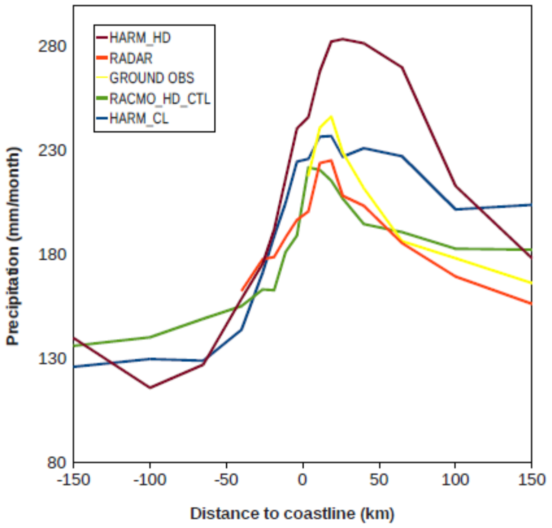


Figure 5.6: *Accumulated precipitation rates for the first three weeks of August 2006 as a function of the distance to the coast for: HARMONIE Hindcast (brown), HARMONIE Climate (blue), RACMO Hindcast (green), ground observations (yellow) and radar observations (red).*

In order to further explore the reasons for the higher precipitation amounts in HARMONIE as compared with observations and RACMO, it is useful to consider a simple moisture budget analysis of the total atmospheric water vapour in the whole domain. If we denote the total amount of water vapour in the atmosphere by Q, the moisture budget equation reads

$$\frac{\partial Q}{\partial t} = E - P + MC \approx 0 \,.$$

On the left hand side we have the storage term, which is equal to the surface evaporation E minus the precipitation *P* plus a moist convergence term *MC* due to the inflow of moisture at the boundaries of the domain. For longer periods such as a month the storage term is much smaller than the sink and source terms which are approximately in equilibrium. As the lateral boundary conditions are the same for RACMO and HARMONIE we expect that the moist convergence MC is the same for these models, at least at the scale of the whole model domain. That implies that for a timescale of a month and on a spatial scale of the whole model domain, *E-P* has to be equal in RACMO and HARMONIE. Therefore, since HARMONIE simulates higher precipitation amounts than RACMO it should also have higher surface evaporation values. Figure 5.7 shows the evaporation rate as a function of the distance to the coast. The RACMO simulation has a typical surface evaporation rate of 70 mm/month in agreement with measurements at the Cabauw measurement site. The HARMONIE simulations on the other hand have much higher surface evaporation rates of around 100 mm/month. This difference is due to a too high soil moisture in HARMONIE and likely the cause of the overprediction of the surface evaporation and hence the precipitation of HARMONIE inland. Furthermore it is surprising to see the large difference of surface evaporation of moisture over sea between HARMONIE and RACMO.

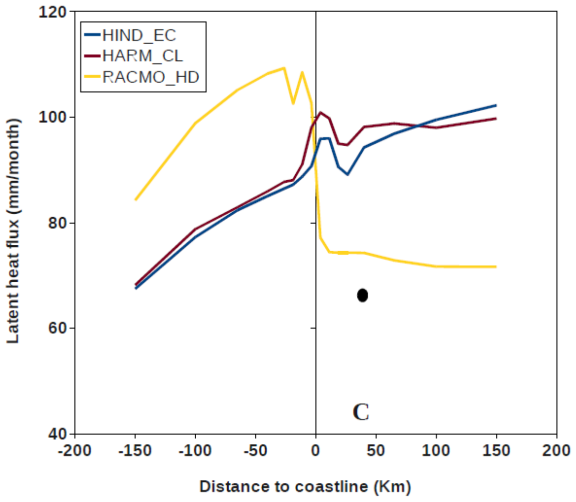


Figure 5.7: *Evaporation rate as a function of distance to the coast for the HARMONIE simulations and the RACMO hindcast. As a reference the evaporation rate measured at the Cabauw site (black dot) is also shown clearly indicating the overestimation of the HARMONIE simulations inland.*

5.5 Sensitivity of precipitation to the sea surface temperature

All simulations described in Section 5.4 gave much higher precipitation amounts than the climatological values and it has been hypothesised that this is due to the higher SST's. In order to further investigate the role of the SST on the enhanced precipitation we have made two additional HARMONIE sensitivity climate simulations: one in which the observed SST's are increased with 2K and one in which they are decreased by 2K. All the other details of the HARMONIE climate runs are identical to the standard run.

Table 5.2: *Total precipitation amounts for the sensitivity simulations.*

	3 weeks	**August 2006**
Experiment	**Precipitation (mm)**	**Precipitation (mm)**
HARMONIE_CLIMATE	144	224
HARMONIE_CLIMATE+2K	145	244
HARMONIE_CLIMATE-2K	121	186

Table 5.2 shows that changing the SST's has indeed a strong impact on the monthly mean precipitation: The +2K-run gives an increase of 20 mm while the -2K-run gives a decrease of 38 mm for the monthly mean precipitation. Moreover if the spatial distribution of the monthly mean precipitation is inspected (see figure 5.8) it is clear that the most significant differences occur in the coastal region. This is further confirmed if we repeat a similar analysis of the monthly mean precipitation as function of the distance to the coast (see figure 5.9). Indeed higher SST's give larger precipitation amounts in the coastal region, but inland beyond 100 km from the coast there is no effect of the SST on the precipitation amounts, all in agreement with our hypothesis.

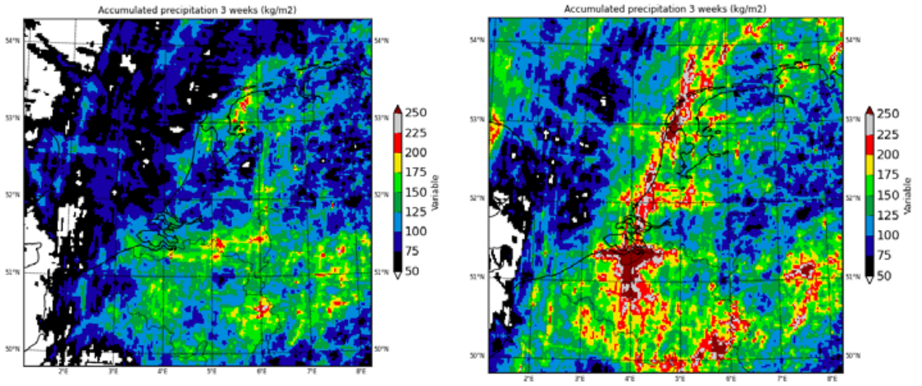


Figure 5.8: *Integrated precipitation for the first three weeks of the HARMONIE Climate sensitivity simulations during which the SST's have been decreased by 2K (left panel) and increased by 2K (right panel).*

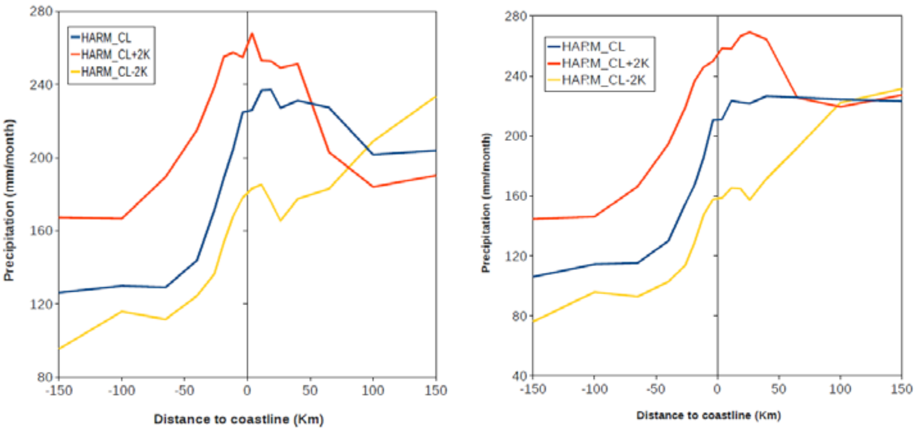


Figure 5.9: *Accumulated precipitation for the first three weeks of August 2006 (left) and for the whole month of August (right) as a function of the distance to the coast for: HARMONIE Climate (blue), +2K (red) and -2K (yellow).*

5.6 Impact of higher resolution sea surface temperatures

All the HARMONIE runs discussed so far are based on SST's that were derived from the ECMWF analysis and are displayed in figure 5.10. As an alternative we have investigated the impact of using observed higher resolution SST's based on NOAA satellite observations. These SST's are shown in the right panel of figure 5.10 along with a difference plot. This shows that the NOAA observations prescribe higher SST's up to 3K in especially Lake Yssel and the Wadden Sea. Also for the near coastal North Sea area the NOAA derived SST's are warmer up to 1 K.

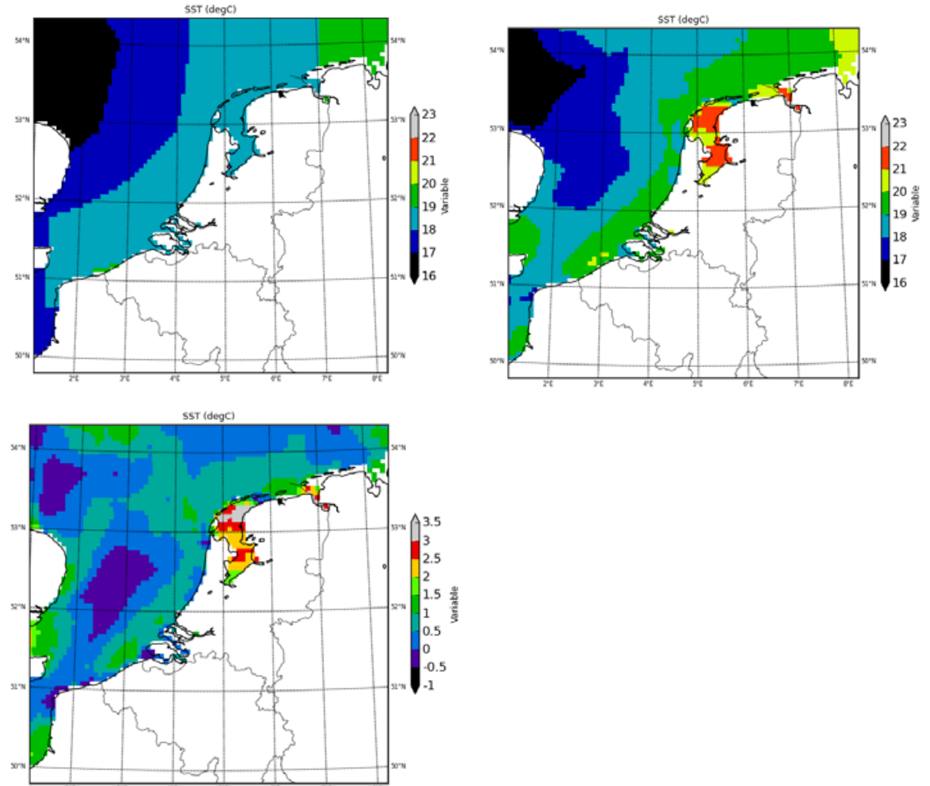


Figure 5.10: *Top left panel: The monthly averaged SST used in all model simulations as provided by the ECMWF analysis. Top right panel: Higher resolution SST based on NOAA satellite observations. Lower panel: Difference plot of the SST's.*

At the moment it is not yet technically possible to feed HARMONIE with the higher resolution SST's. So in order to assess the impact of NOAA based SST's we compare in figure 5.11 the monthly precipitation for RACMO hindcasts.

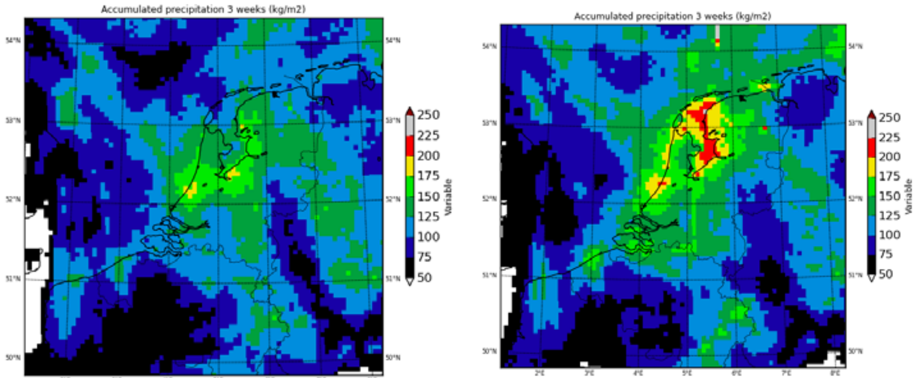


Figure 5.11: *The monthly-accumulated precipitation of a RACMO Hindcast using (left panel) the ECMWF SST analysis and (right panel) NOAA based SST's.*

The results show clearly the impact of the different SST fields that are prescribed. Especially the higher SST's over the lake Yssel and to a lesser extend the higher SST's of the North Sea result in higher precipitation amounts in the coastal regions. This is further quantified in figure 5.12, in which the accumulated precipitation is analysed as a function as a distance to the coast. The NOAA observed SST's clearly result in more precipitation over the North Sea but also in the coastal regions over land. In fact the precipitation amounts overestimate the observations. However the overall message is that higher resolution has a significant impact and hence should be included in operational forecasts. For future climate runs this indicates that an interactive North Sea model should be implemented since SST's provided by coarser resolution global climate models will underestimate the SST's of Lake Yssel and the North Sea temperatures near the coast.

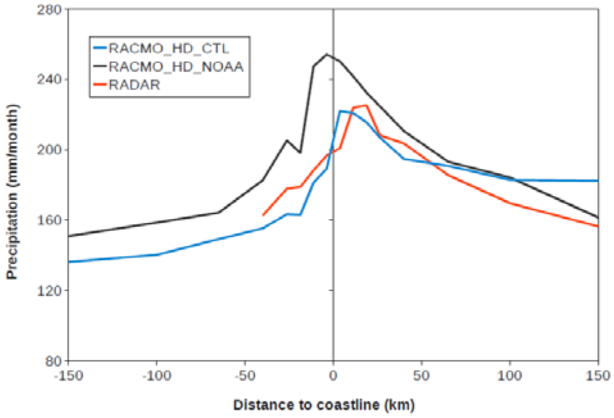


Figure 5.12: *Accumulated precipitation as a function of distance to the coast for RACMO with ECMWF analysis SST (red) along with improved higher resolution observed SST's (yellow). Observations are included as a reference (green).*

5.7 Conclusions and outlook

HARMONIE has been technically suitable for being used as a regional climate tool and the simulation of the August 2006 period should be viewed as the first attempt to use and evaluate HARMONIE for such a purpose. This study has demonstrated for the first time that a climate run of a month does give realistic precipitation amounts. In fact the results show that the precipitation characteristics for the free climate run give even similar results than the hindcast. Also the results show that the higher resolution also give maximum precipitation slightly land inward, a result that could not be obtained with the coarser resolution runs of RACMO. On the other hand both the precipitation amounts and the precise location are at the moment less accurate than RACMO. This is partly due to the soil moisture. Despite the fact that the same soil moisture fields from the ECMWF analysis have been used to initialise HARMONIE as has been done for RACMO, we have found substantial larger evaporation rates over land in HARMONIE and lower values over sea. We will further look into the moisture budget on a more local scale and compare this with observations, reanalysis and Large Eddy Simulations in order to make the model better capable for supplying an improved moisture budget.

In subsequent studies we will also further look into this. We also will look deeper into the cloud processes themselves on a case basis, especially for days in which there are large differences between RACMO, HARMONIE and the observations. We will further look into the auto conversion, rain evaporation and the subgrid turbulence and convection to determine the sensitivity of these processes on the observed precipitation.

We will also make HARMONIE suitable for using the higher resolution observed SST’s for which it has been demonstrated that it has a significant impact on the precipitation results.

6 Model verification – a new approach

6.1 Background

The interest in high-resolution numerical weather prediction is mainly driven by the presumed ability to skilfully predict extremes in critical weather situations. Heavy precipitation and strong wind may be very local phenomena, for which even a grid spacing of several km could be too coarse to resolve. A nice example of such an event is our cold pool case [cf. Mendez-Gomez et al., 2012, case April 30th 2006], in which we demonstrated that HARMONIE can resolve the dynamical structure of the cold pools provided that the horizontal grid resolution of the model is finer than 2.5 km.

The higher resolution of the models also poses a challenge for the verification of the forecasts. We know that higher spatial resolution precipitation forecasts often look more realistic, but the question is whether they are more accurate? Conventional methods, such as point-to-point verification, often fail to show the benefits of such forecasts[2]. For example, when the timing or location of a shower is only a few minutes or kilometres off, a point-to-point comparison will see this as a double mismatch: a shower is forecasted where it is not observed, raising a `false alarm', and the observed shower is not forecasted, counting as a `miss'. Nevertheless, these may be very useful forecasts, giving relevant information to most of the end-users. So how can we provide information to judge whether the additional computational expense of running a high-resolution model is justified. The main question that has to be raised here is: Which verification measures are adequate to assess the forecast skill in this case?

The question of verification and how output from a kilometre-scale model should be interpreted and presented to the user, relates way back to the concept of predictability. Although our models initial conditions are improved all the time, we know we can never get them exactly right. Furthermore, it is also not possible to eliminate all deficiencies in the representation of physical and dynamical processes in the forecasts. A finer spatial model resolution introduces faster-growing errors because the smaller scales that are represented by the model become unpredictable more quickly. Despite the degradation of the smallest represented scales, we hope that the forecasts over the larger scales are still skilful. From this perspective our previous question should be reformulated as: Which modelled scales are skilful and which verification measures are suited to assess this skill?

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[2] Note that point-to-point verification of high-resolution forecasts of parameters other than precipitation may still be very appropriate.

In Impact several new verification methods are studied that try to circumvent problems that arise with conventional verification, such as the double penalty problem [van der Plas et al., 2011]. The new methods are suited to assess which scales are skilful in high-resolution precipitation forecasts. In this chapter, two different approaches are described: 1) The Fractions Skill Score (FSS) [Roberts and Lean, 2008], which values a forecast if a criterion (e.g. 1 hour accumulated precipitation > 5 mm) is met in a neighbourhood of the observed event, and 2) The Method for Object-based Diagnostic Evaluation (MODE) [Davis et al., 2006], in which objects are defined and compared in both forecasts and observations. Both methods provide information about the displacement errors and forecast skill. In this chapter, the application of these two methods is demonstrated for a period with several events with convective precipitation. The software that we used in Impact to apply these methods is the Model Evaluation Tool (MET), developed by the Developmental Test bed Centre (DTC) at NCAR [Davis et al., 2006 and 2009]. But first, in section 6.2 of this chapter, some standard verification results, using conventional methods, for model parameters such as temperature and wind are presented.

6.2 Standard verification results

Standard verification of two different HARMONIE suites, called ANJAN and ECJAN, that are hosted at the ECMWF, resp. using HiRLAM and ECMWF boundaries, is done using a number of observation stations. This is part of a standard verification utility at the Danish Meteorological Institute (DMI), which generates a simple albeit brief report of how the most basic parameters score over a month time. Some of the results of the verification will be discussed here, using the November period in 2011 as an example. However, most of these results apply equally well to the rest of the year.

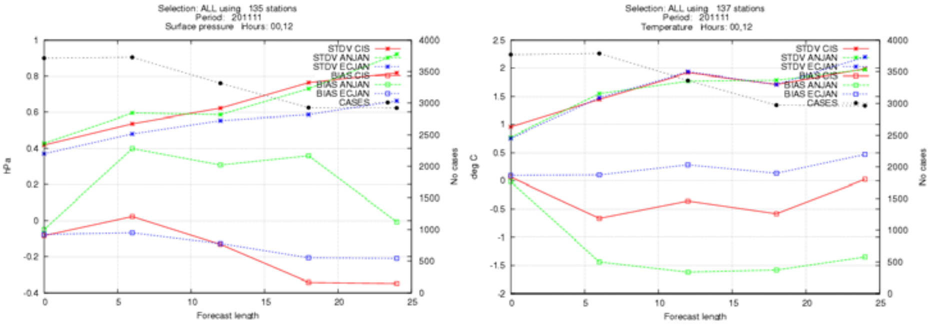

***Figure 6.1:** The bias (squares) and standard deviation (stars) of the MSLP (left) and 2m temperature (right) as a function of the forecast lead-time in November 2011. HiRLAM CIS run in red, ANJAN in green and ECJAN in blue.*

The Mean Sea Level Pressure (MSLP) is one of the most common parameters to verify. If we look at figure 6.1 we see the bias (squares) and standard deviation (stars) of the HiRLAM model (CIS) and the HARMONIE model (ANJAN, ECJAN). Standard deviation and magnitude of the bias are expected to increase with lead-time. The anomalous bias for the ANJAN run is probably related to the bias in the 2m temperature (same figure, right panel), which is due to an issue with soil ice initialisation when HARMONIE is run with HiRLAM boundaries. This issue is under consideration and is probably solved for revision HARMONIE cycle 36h1.4 and up.

Other quantities, such as 10m wind and cloud cover, as shown in figure 6.2, show good results. Here, the ANJAN run produces forecasts with considerably less bias. It is noted that even with the higher resolution and therefore larger variability the HARMONIE standard deviation has still the same order as from HiRLAM.

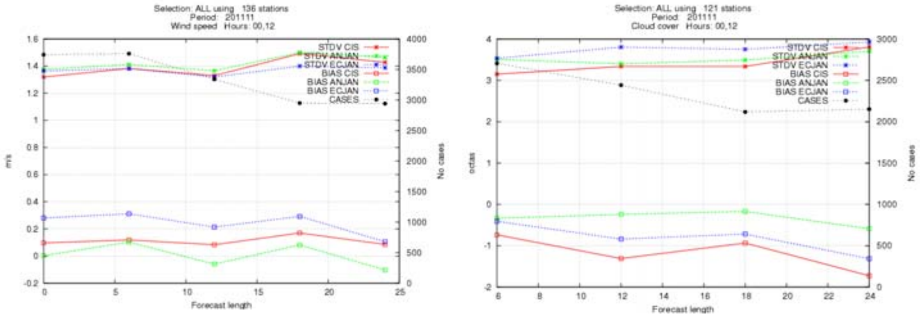

Figure 6.2: *The bias (squares) and standard deviation (stars) of the 10m wind (left) and cloud cover (right) as a function of the forecast lead-time in November 2011. HiRLAM CIS run in red, ANJAN in green and ECJAN in blue.*

6.3 A neighbourhood verification method: FSS

The most widely used method to take into account that higher resolution forecasts may introduce localisation errors is the Fractional Skill Score (FSS). The FSS was introduced by Roberts and Lean [2008]. The method was designed to assess the variation of skill as a function of spatial scale from high-resolution precipitation forecasts. A nice explanation of the FFS method, without using to many formulas, can be found in Mittermaier and Roberts [2010]. Here we have summarized the most important details of the method.

The FSS method attributes merit to a forecast if a certain criterion (e.g. 1 hour accumulated precipitation > 5 mm) is met in a neighbourhood of the observed event. The criterion, or threshold, is first applied to both the forecast and verifying observed field. Then, the neighbourhood of each forecast grid point is compared to the neighbourhood of the observed grid point, using the ratio of grid points exceeding the threshold within the neighbourhood. This is repeated for all grid points and then successively larger neighbourhoods until the entire domains are compared. As a result, the FSS compares forecasts and observations over different sized neighbourhoods. In this way we can determine how the forecast skill varies with neighbourhood size and we can determine the smallest neighbourhood size that provides a forecast with sufficient skill. The FSS score is minimal for a neighbourhood size of 1, i.e. pixel-per-pixel comparison, and tends asymptotically to a ratio of the frequencies of the observed and forecasted events as the neighbourhood extends to the whole domain. Only when the forecast is unbiased, this limit equals 1. But, typically forecasts are biased, because the number of grid points in the forecast is different from the comparing observation, and the FSS for the whole domain is less than 1. Roberts and Lean [2008] also show that a skilful spatial scale is derived for when $FFS > 0.5 + f/2$, where f is the observed fractional rainfall coverage over the domain (the so-called wet-area ratio). This value of FFS represents a lower limit of useful scales. If f is not very large (and it typically is not for a large domain), a value of 0.5 can be used as a lower limit.

Using neighbourhood aggregation over an area around a pixel, it is also possible to compute other well-known scores, which are traditionally derived from a contingency table (cf. table 6.1). The MET suite provides most of the relevant scores, but the ones that will be used in this chapter are the Hanssen-Kuiper discriminant (HK) and the Gilbert Skill Score (GSS), the latter also known as the Equitable Threat Score (ETS). The Hanssen-Kuiper discriminant is defined as

$$HK = \frac{a}{a+c} - \frac{b}{b+d},$$

which gives a measure of how well the areas with precipitation are distinguished from the areas without. The Gilbert Skill Score then is

$$GSS = \frac{a-a_r}{a+b+c-a_r},$$

where the so-called random hits $a_r = (a+b)(a+c)/(a+b+c+d)$ or hits associated with random chance, is used to correct for different climate regimes. In this way scores for wetter periods or areas can be compared to the same metric for dryer periods.

***Table 6.1:** Standard 2x2 contingency table for categorical Yes/No forecasts. In the table A, B, C and D, respectively represent the number of Hits, Misses, False Alarms and Correct Rejections.*

		Observed	
		Yes	No
Forecast	Yes	A	B
	No	C	D

The FSS as described above can be used for assessing the skill of a single case study, or it can be aggregated to assess many cases together. The forecast skill computed in this way, however, is rarely uniform across the forecast domain. Therefore, a neighbourhood verification method such as the FSS cannot directly focus on individual objects. The score is influenced by all objects of interest (i.e. which exceed the chosen threshold) within the forecast domain at the time. Therefore, by definition, the metric is one of aggregated skill, which can be extended to assess a whole sequence of forecasts, say within a given month.

6.4 An object based verification method: MODE

The method for object-based diagnostic evaluation (MODE, [Davis et al., 2006]), which has been applied in Impact, has a quite different approach. This is best illustrated by looking at some of the difficulties associated with diagnosing forecast errors using standard verification approaches. Figure 6.3 shows five examples of forecast (F) – observation (O) pairs, with the forecasts and observations represented as areas. For a forecast user, the cases in figures 6.3a–d clearly demonstrate four different types or levels of “goodness”: (a) appears to be a fairly good forecast, just offset somewhat to the right; (b) is a poorer forecast since the location error is much larger than for (a); (c) is a case where the forecast area is much too large and is offset to the right; (d) shows a situation where the forecast is both offset and has the wrong shape. Of the four examples, our forecasters and model developers will definitely choose that case (a) is the "best." Given the perceived differences in performance, it is dismaying to note that all of the first four examples have identical basic verification scores[3]: POD = 0, FAR = 1, CSI = 0. Thus, the verification technique is insensitive to differences in location and shape errors. Similar insensitivity could be shown to be associated with timing errors. Moreover, example (e) in figure 6.3 —which could be considered a very poor forecast from a variety of points of view— actually has some skill (POD, CSI > 0; FAR < 1), suggesting it is a better forecast than the one depicted in example figure 6.3(a).

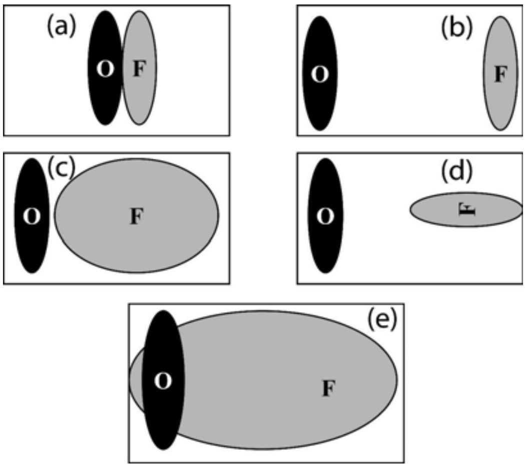

Figure 6.3: *A schematic example of various forecast and observation combinations (a) – (d). These all yield CSI = 0, whereas (e) has positive CSI, but would probably not be evaluated as the best subjectively.*

The MODE approach more directly addresses the skill of forecasts of localized, episodic phenomena, such as rainfall events, than the more traditional verification methods do. MODE identifies "objects" in the forecasted and observed fields that are relevant to a human observer. These objects can then be described geometrically, and relevant attributes, such as location, shape, orientation and size of the forecasted and observed objects, can be compared. In MODE a convolution (smoothing) and thresholding procedure is used to identify the objects. In this procedure, small and potentially uninterested features are filtered out. The resulting objects are then reduced in number and size, sometimes after merging them, so that a few objects of interest remain. Next, forecasted objects are associated to observed objects. For this, we use an interest function that prescribes, on a scale from 0 to 1 (1 being perfect), how closely an attribute of the forecasted object matches the same attribute of the observed object. When the interest is larger than a certain number (here a threshold of 0.65 is used) objects are considered to match. When several ob-

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[3] The basic verification scores are derived from the contingency table 6.1. The probability of detection POD = a / (a+c), the false alarm ratio FAR = b / (a+b) and the critical success index CSI = a / (a+b+c).

jects match to each other above this threshold, the objects are called a 'cluster'. After matching forecasted and observed objects, displacement and shaping errors can be determined, and after aggregating the results from several events, accumulated statistics for errors in position can be constructed and mean error, standard deviation and root-mean-square error, etc., computed. As an example, the output of the MODE algorithm, for one particular time and model is shown in figure 6.4.

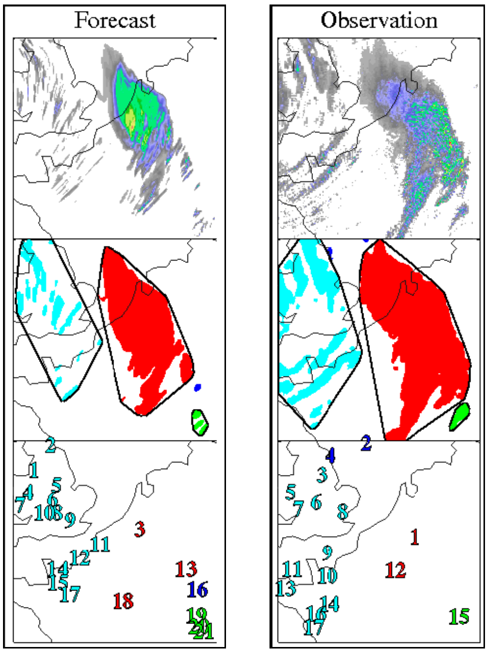

Figure 6.4: *Typical output of the MODE algorithm, here for HARMONIE with HiRLAM boundaries for July 14th, 18:00 UTC: On the left the forecasted precipitation field is given (top: raw data, middle: thresholded and convoluted objects, bottom: objects numbered and coloured by matching criteria with observations). On the right the radar precipitation data is given.*

6.5 Non-standard verification results

The non-standard verification methods that are described in sections 6.3 and 6.4 are applied to verify rainfall forecasts produced by the non-hydrostatic high-resolution model HARMONIE, and compared to the results of the current operational standard HiRLAM. For the latter, the HiRLAM RCR reference run at ECMWF is used. Forecasted fields from both models are compared to the European precipitation radar composite at 4 km resolution. In this study a 10 day period from 6 to 15 July 2010 was chosen. In this period, weather alerts have been issued by KNMI for extreme precipitation at 10, 12 and 14 July. The latter case was also demonstrated in chapter 4, section 4.4.

Model data and observations

The HARMONIE runs for this study were executed on a 400x400 grid with 2.5 km grid resolution and using boundaries from the HiRLAM RCR (approximately 15x15 km resolution) run and from the ECMWF operational run. The runs were initialised by either the HiRLAM RCR or the ECMWF analysis at 00 UTC. However, as some of the HARMONIE prognostic variables, e.g. vertical velocity for convection and the hydrometeors, are not initialised, this will effectively be considered as a `cold start'. Model starting times are 00, 06, 12 and 18 hours

UTC, with a 12-hour lead-time. A spin-up time of 3 hours is taken into account, so the data of T+003 until T+012 are considered in this particular study.

The choice for the European composite radar product RADNL23 can be motivated by the assertion that in this pilot study we primarily concern ourselves with the distribution of (extreme) precipitation. It is recognised that this data is aggregated from various different radar installations, giving rise to quantitative differences for the different areas. Also, over the North Sea radar clutter can give rise to complications for the verification methods, especially the object-based methods. As the scatter has very little spatial extent but may have considerable intensity, the convolution step in MODE tends to overestimate these areas. A more reliable radar product may one day be available as a result of the OPERA project and by cross validating with MSG satellite data during daytime.

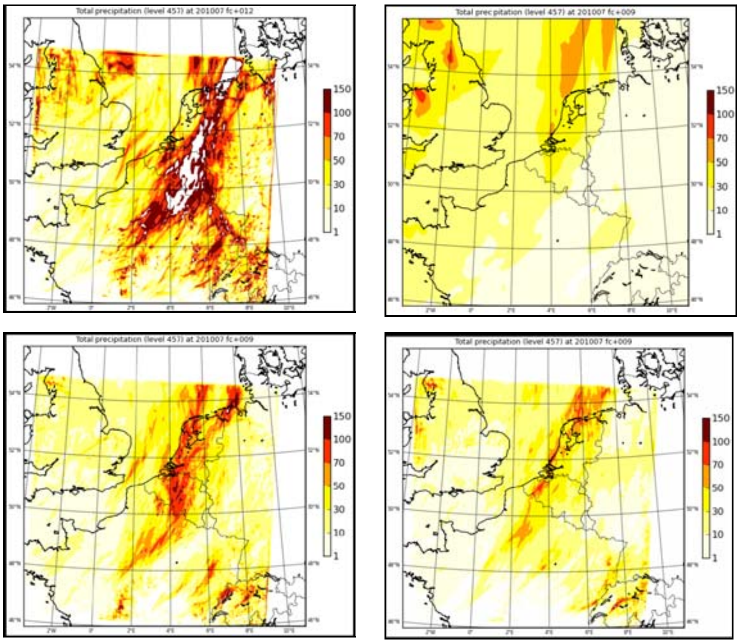

Figure 6.5: *Total accumulated precipitation for the period 6 – 15 July 2010. Top left: radar data, right: HiRLAM RCR. Bottom left: HARMONIE with HiRLAM boundaries, right: HARMONIE with ECMWF boundaries.*

Results

First of all, the total precipitation over the 10 day period can be compared, see figure 6.5. The radar shows the largest amount of rain, also with the largest amount of variation. The HiRLAM RCR data gives a considerably smoother picture. Here we point out that the data shown here is already re-sampled to the HARMONIE grid, giving rise to some obvious re-sampling artefacts. The HARMONIE data resembles the radar data more closely, where the run nested in the HiRLAM model gives higher quantities, especially in the band of intense rain that crossed Belgium and the Netherlands. These numbers can be summarised in the histogram in figure 6.6. The distribution of the radar data is shifted towards higher intensities than the model data, whereas the HARMONIE runs have more dry pixels, reflecting the tendency of the model to under represent light rain. The maximum in the distribution in the HiRLAM RCR precipitation around 20 mm can probably be attributed to the coarse resolution of the model setup.

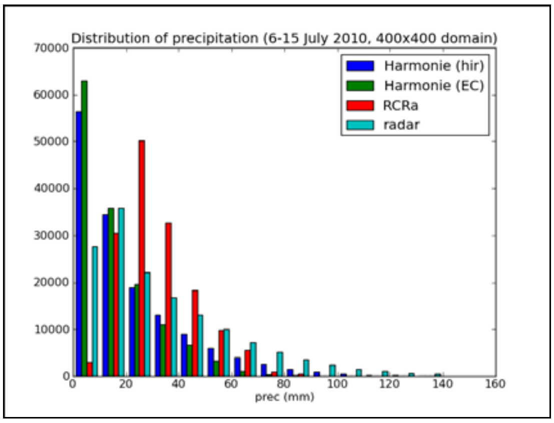

Figure 6.6: *Histogram of the total accumulated precipitation for the period 6 – 15 July 2010.*

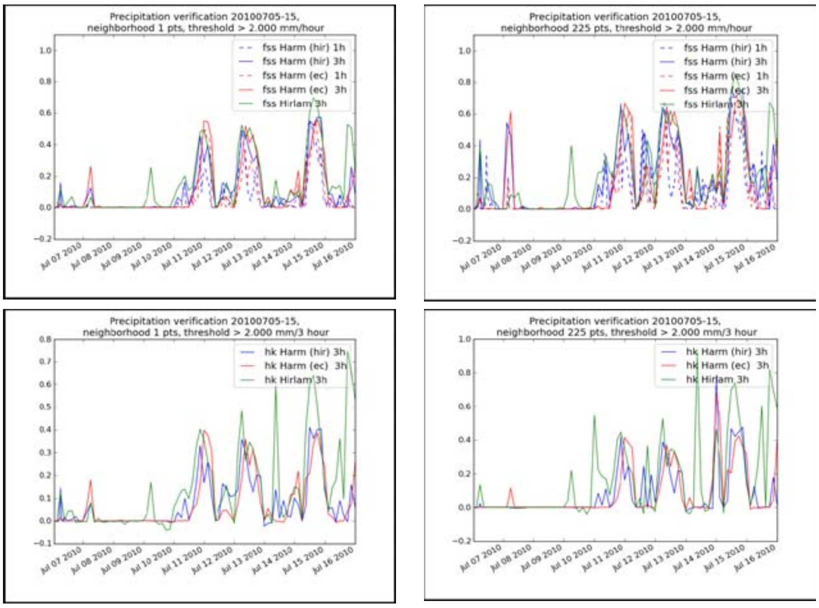

Figure 6.7: *Time series of FFS (top panel) and the HK discriminant (bottom panel) for precipitation over 2 mm/3h, with a neighbourhood size of 1 pixel or 2.5x2.5 km (left) and 15x15 pixels or 37.5x37.5 km (right). The green line represents the RCR run data, blue HARMONIE with HiRLAM boundaries and red HARMONIE using ECMWF boundaries.*

A time series of the FSS and the Hanssen-Kuiper discriminant is shown in figure 6.7. We compare the different runs taking either a neighbourhood size of 1 by 1 pixel, the classical CTS score, or 15 by 15 pixels, smoothing the data over an area of 37.5 by 37.5 km. This has been taken as the upper limit, assuming that beyond this area one cannot speak of a resolution effect in the quality of the models. In this figure the scores for precipitation of more than 2 mm per three hours is shown.

The three events with heavy precipitation are clearly visible in figure 6.7. The scores are comparable for the three models. For the 1 pixel neighbourhood size, i.e. pixel-per-pixel comparison, shown on the left, HiRLAM scores generally slightly higher for the large scale events, and also picks up an event at the 8th of July. This holds for both the FSS and the HK discriminant score. Increasing the neighbourhood size, to 15 by 15 pixels on the right side, results obviously in increasing scores, but the same qualitative picture remains. The scores of the HARMONIE runs increase a bit more than those of the HiRLAM RCR run.

For higher precipitation intensities, e.g. >10 mm/3h, the difference between the models is more remarkable, see e.g. figure 6.8. Here we chose to show the Gilbert Skill Score (GSS) and the HK discriminant for a neighbourhood size of 15 times 15 pixels. For smaller neighbourhoods the qualitative picture is the same, but then there are very few matched events. For these intensities, the HARMONIE models show more skill than the HiRLAM run. This is to be expected, as the spatial extent of extremes becomes of the order of the grid size, so that in this case 10 mm/3h for an entire HiRLAM RCR grid box becomes improbable.

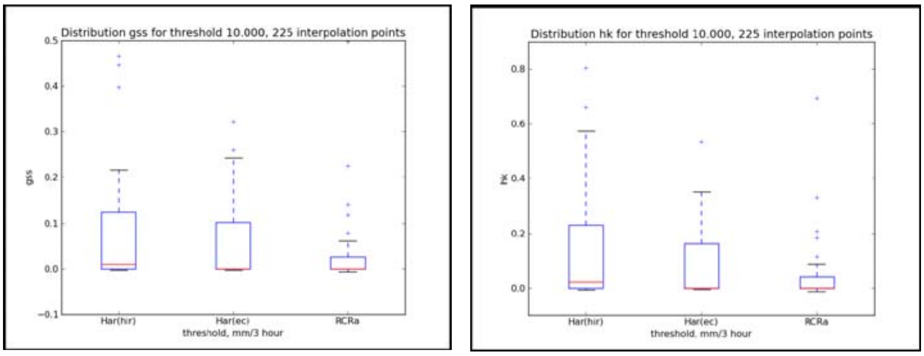

Figure 6.8: *Box plot of the GSS (left) and the HK discriminant (right) for precipitation over 10 mm/3h and a neighbourhood size of 15x15 pixels.*

If we look at the MODE analysis, we first observe that the process of grouping precipitation features into objects of a certain minimum size makes it easier to do visual, subjective verification. Per case or time step one may compare certain attributes of objects one is interested in, such as the amount of interest between forecasted objects and its observed counterparts, or the centroid distance. However, to condense this information into a single score over the entire time range is less straightforward. Furthermore, we note that the configuration of MODE has many degrees of freedom. Some settings, such as the radius of the convolution kernel, which determines the amount of smoothing in object identification, can make a substantial difference in how the objects come out.

In figure 6.9 (left panel) we show e.g. the scores for the `centroid distance', i.e. the distance of the `centre of mass' of an object or cluster with its associated counterpart, in this case for the cluster with the largest area in every time step. The results seem to indicate that the HARMONIE forecasts produce precipitation events that are closer to the observed ones than the HiRLAM forecast. However, the objects or clusters are not tracked in time, so this naive attribute does not tell whether the largest cluster at one time step is related to the largest cluster in the next. Also, the grouping of objects into a cluster is not always very consistent in the sense that storms that belong to different clusters in one time step may coalesce into the same cluster and vice versa.

One more consistent method to construct a score was proposed in [Davis et al., 2009], using the median of the maximum interest (MMI) of the whole domain. The matching procedure computes the interest between all features, and considers it a match when this number is above a certain, user-defined threshold. By considering the median of all these interest values, we have a measure that reflects how well the forecast performed for a given moment, and that can be used to compare between different models and during different (dryer and wetter) periods. The results for this particular case are shown in the right panel of figure 6.9. It is remarkable that the three models perform almost indistinguishable for this particular score.

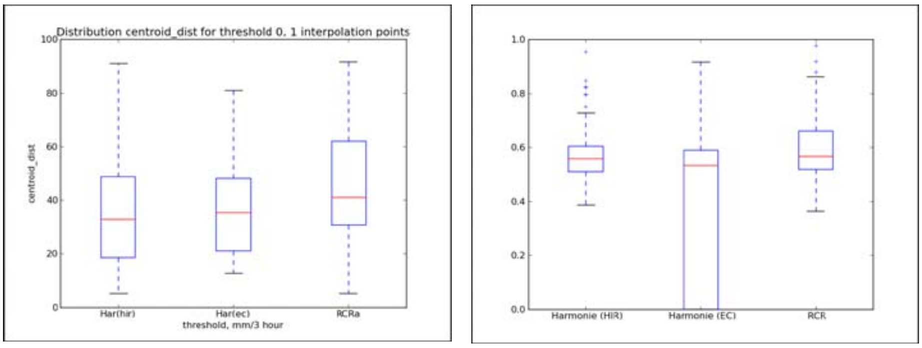

Figure 6.9: *Box plot of the centroid distance of the largest cluster in a particular time step (left) and MMI scores (right) of HARMONIE using HiRLAM boundaries and the HiRLAM RCR run over the 10-day period.*

6.6 Conclusions

A few new verification methods have been applied to HiRLAM and HARMONIE model data that correspond with convective weather events, using the European composite precipitation radar product to verify against.

The high level of detail in the forecast would suggest that classical methods, such as (neighbourhood) contingency table statistics (CTS), are less well equipped to attribute the forecasted precipitation features to its observed counterparts than the more flexible object-based methods, such as MODE. However, the qualitative picture that arises when comparing the scores of HARMONIE and HiRLAM shows that using the former CTS-based method, with e.g. the HK discriminant, gives relatively more credit to the higher resolution forecasts than for this specific choice of MODE results. The higher resolution of the HARMONIE model does give a better representation of the more extreme events (> 10 mm/3h) than HiRLAM. This is one of the expected advantages from a high-resolution model that properly takes into account the dynamics on the smaller scales. These higher precipitation intensities were hardly present in the HiRLAM data as a result of the coarser resolution.

It is noted that this is just a preliminary study with a very modest amount of data. Furthermore, the output of the MODE algorithm is so rich, that obviously more effort should be invested into combining the attributes in such a way as to produce a score that gives intuitive results and can be compared over a variety of cases.

7 Outlook

7.1 Conclusions

In this project we learned that the new high resolution non-hydrostatic atmospheric model HARMONIE is very well suited to: a) Provide more accurate and more detailed weather predictions for Schiphol airport, and b) Compute the effect that climate change has on local critical weather conditions at the airport;

We demonstrated that the HARMONIE model does not only add smaller scale information to our present day operational weather model HiRLAM and the climate model RACMO, but that it also adds a number of relevant physical processes that directly affect the climate in the Netherlands on local and regional scale, particularly in the summer (in the winter large scale dynamics dominates). Furthermore, when the domain size of the model is large enough the model is also more accurate in the timing and intensity of extreme events. Finally, HARMONIE is capable to represent small regions with very intense weather, e.g. very high wind speeds, which are mostly absent in HiRLAM.

Some aspects of the model should be further investigated. The representation of fog and low clouds in the model is sensitive to small errors. We believe that this is due to the coarse vertical resolution that is used in the standard setup of HARMONIE.

The HARMONIE model is also suited to compute the effect of a warmer climate on future weather. However, local critical weather parameters such as extreme rainfall, heavy wind and high temperatures, are very sensitive to land surface and sea surface data that are used by high-resolution models such as HARMONIE. Moreover, HARMONIE is not very flexible in the specification of the surface conditions and the use of alternative data sets for that.

HARMONIE has also been evaluated for its skill to be used as a regional climate tool. To this purpose the August 2006 period, during which a record amount of precipitation was observed, particularly near the coast, has been studied. The results show that a climate run of a month does give realistic precipitation amounts. Furthermore, HARMONIE is capable to simulate the precipitation peak slightly land inward, a result that could not be obtained with the hydrostatic model RACMO. On the other hand, we have seen that HARMONIE overpredicts the precipitation amounts, which is most likely caused by too high soil moisture values in the model.

A few new verification methods have been studied in Impact, which we believe are more suited to demonstrate the skill of high-resolution models such as HARMONIE. First results show that the new methods give more credit to the higher resolution forecasts of HARMONIE than the more conventional verification methods do.

7.2 Recommendations

The following recommendations are made for future research:

- *Projections of climate scenarios to local scales*: For a number of short-term weather events, or longer (e.g. monthly) periods, future analogous of contemporary extremes (e.g. in precipitation, wind, gusts, hail and thunder) should be computed with HARMONIE at a high resolution (2 km scale) and consistent with present day scenario predictions for a future climate.
- *A better understanding of extreme shower intensity and local precipitation extremes*: Investigation of (changes in) precipitation extremes at different spatial and temporal scales, with a focus on hourly precipitation intensity and coastal effects in HARMONIE. This is important for Schiphol as the airport is situated near the coast.
- *An investigation of the performance of HARMONIE for predictions of severe hail and snow*: These precipitation types may hinder airport operation and/or cause damage to aircraft. Aspects that should be considered are the intensity and distribution of these precipitation types in space and time.
- *An investigation of the performance of HARMONIE for high wind speeds and sudden strong fluctuations in the wind (gusts) at the airport and in its vicinity*: Validation of the 4D wind field at the airport (surface and upper-air winds) in space and time, using local and neighbouring wind observations.
- *A better understanding of the effect of physical processes and numerical setup options on the success of mesoscale models to model radiation fog*: radiation fog depends on many processes that all critically interact on relatively short time scales. Further research is required to investigate whether current parameterizations for physical processes are adequate for modelling radiation fog. Also, further research is required to which extent the details of the numerical setup of the experiment such as the extension of the domain and the horizontal and vertical resolution determine the success of mesoscale models to forecast fog.
- *A better understanding of the influence of surface conditions on local climate and the sensitivity of the HARMONIE model therein*: Investigation of the impact that land surface, heterogeneity and changing surface conditions (e.g. influence of urbanization), and the sea surface (e.g. sea surface temperature and changes therein) have on our present and future climate.
- *Increasing the flexibility of HARMONIE to use different, or modified, data sets for the specification of the surface conditions*: Adapt HARMONIE so that different, or modified, data sets can be used for the description of surface conditions such as land use type (e.g. sea, lake, nature and urban areas) and coverage, soil/vegetation type and coverage, land-water boundaries and sea surface temperature.
- *International collaboration on climate modelling with the Rossby Centre at SMHI*: Establish cooperation with the regional climate group at the Rossby Centre for joint research with HARMONIE on climate applications and future weather issues on regional and local scales.

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Climate-proofing the Netherlands and to create a sustainable
Knowledge infrastructure for managing climate change

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