TECHNICAL MEMORANDUM

543

# Improvement in the capturing of short-range warm season orographic precipitation in the ECMWF model

Andrew Orr and Peter Bechtold

Research Department

March 2008

To be published in a special issue of *Meteorology and Atmospheric Physics* on the 29th International Conference on Alpine Meteorology (ICAM), Chambery, France 2007



European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

**Series: ECMWF Technical Memoranda**

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/publications/

Contact: library@ecmwf.int

## Abstract

ECMWF short-range deterministic forecasts at T799 resolution (approximately 25 km horizontal resolution) of warm season convective precipitation over the Rockies and the Alps are compared with high-resolution observations. Both a former model cycle (30R1, operational in the first half of 2006, the first model version at resolution T799), and a more recent cycle (32R3, operational from November 2007) of the ECMWF Integrated Forecasting System (IFS) are investigated in order to assess the impact of substantial modifications to the model's convection and radiation scheme on the precipitation forecasts.

With 30R1, the strong diurnal cycle of precipitation over the Rocky Mountains is not captured. Significant improvements are obtained with 32R3, including the capturing of a nocturnal rainfall maximum over the Great Plains associated with organised propagating mesoscale convective systems. Part of the improvements are due to non-local feedbacks where increased convective mid-tropospheric heating leads to improved large-scale circulations (moisture advection) maintaining the convection.

By contrast, over the Alps both versions of the IFS under/over estimate the precipitation for values smaller/larger than 10 mm/day. This reflects the different meteorology and the east-west orientation of the Alpine mountains, where compared to the Rockies more quasi-stationary convective systems, form in a generally moister large-scale environment, and where the large-scale horizontal advection of moisture is less crucial. However, it is suggested that here the overestimation of precipitation is linked to excessive low-level blocking.


# 1. Introduction

The distribution of precipitation is strongly affected by orographic forcing. The relatively low skill of deterministic forecasting of warm season continental precipitation (e.g. Olson et al., 1995) suggests an inability to accurately capture this process.

Over the Rockies, warm season precipitation is characterised by a distinct maximum in mid-afternoon convective precipitation along its lee (eastern) slopes (Wallace, 1975). This influences rainfall on a much larger scale, as the rainfall maximum propagates east through organised mesoscale convective systems, resulting in a nocturnal rainfall maximum over the Great Plains (Carbone et al., 2002). These systems have a phase speed considerably faster than synoptic systems, and can span from 1000 to 2000 km. The pronounced diurnal cycle over western and central United States is often poorly represented by Numerical Weather Prediction (NWP) models (Davis et al., 2003), partly because the models are unable to capture the complex localised thermal upslope and downslope winds (e.g. Toth and Johnson, 1985) that contribute to the initiation of convection (Banta and Hanson, 1987).

Previously, Cheinet et al. (2005) assessed ECMWF Integrated Forecasting System (IFS) cycle 28R1 (released in March 2004) T255 horizontal resolution (80 km) 60 vertical level warm season forecasts over western and central United States against stage-IV precipitation data. Stage-IV data is a combination of radar and rain gauge precipitation measurements covering the continental United States, with a spatial resolution of 4 km. The authors showed that the mid-afternoon precipitation maximum was insufficient and occurred too early, and that the nocturnal propagation was lacking. Furthermore, they noted a strong dry bias in the model which they partly linked to an underestimation of the nocturnal low-level jet.

Over the Alps, by contrast, both large-scale precipitation and convection contribute to warm season precipitation. Cherubini et al. (2001) assessed IFS cycle 21R2 (released August 1999) T319 (60 km) 60 level forecasts against 24-hourly accumulated precipitation from the high-resolution (25 km) rain gauge (roughly 5000) observations for the Mesoscale Alpine Programme (MAP) special observing period (Bougeault et al., 2001). The authors concluded that the model overestimates precipitation over the Alpine region for values larger than 10 mm/day. Using the same model, resolution and observations, but focusing solely on the Alps, Pedemonte et al. (2005) showed that the IFS correctly predicts the timing of precipitation events, and was good at predicting light rains, but less effective in forecasting moderate and heavy rain. Similarly, Keil and Cardinali (2004) showed that over the Po valley region of the Alps that this model version captured the timing of precipitation events, but overestimated moderate and heavy precipitation. However, the comparison improved using IFS cycle 24R3 (released in January 2002) T511 (40 km) 60 level forecasts.

However, since these studies, many improvements to the physical parameterisations of the IFS have been implemented, and the operational model is now run at a horizontal resolution of T799 (25 km) and 91 levels. Therefore, it is necessary to assess again the IFS performance in forecasting warm season precipitation over orography. Both the Rockies and Alps will be investigated as these regions are characterised by a markedly different climate and flow regimes.

## 2. Model, observations, and method

The simulations considered here use cycles 30R1 and 32R3 of the IFS, the former being released in February 2006, whereas the latter became operational in November 2007.

30R1 was the first cycle to run at resolution T799 and 91 levels. It includes a convection scheme based on a mass-flux formulation and a bulk cloud ensemble model originally developed by Tiedtke (1989) and further developed by Bechtold et al. (2004) to include a trigger function that tests model layers in the lowest 350 hPa (this detects the potential development of deep convective clouds due to elevated unstable layers, which particularly occur during nighttime).

In 32R3 the convection scheme was further revised to include an implicit numerical description of convective transports, and in particular by formulating a quasi-linear scheme where the entrainment no longer depends on the large-scale moisture convergence, but is proportional to the environmental relative humidity. This, together with increased (decreased) rain evaporation over water (land), and the introduction of a variable convective CAPE (Convective Available Potential Energy) adjustment time, proportional to the convective turnover time, allowed the model to break the former strong and detrimental coupling of the deep convection with the large-scale flow (omega field). Tests showed that these modifications alleviate many of the previous IFS deficiencies in representing tropical convection and its variability (tropical waves), including the land-sea contrast in convection.

Furthermore, 32R3 differs from 30R1 by a new radiation scheme (McRad) (introduced originally in 32R2 in June 2007) which includes an improved description of the land surface albedo from MODIS observations, the Monte Carlo Independent Column Approximation (McICA) of the radiation transfer in clouds, and the RRTM short-wave scheme (Morcrette et al., 2007). The new radiation scheme better represents the surface shortwave radiation and produces a stronger cloud-radiation feedback. Additionally, 32R3 takes into account ice-supersaturation (introduced originally in 31R1 in September 2006), therefore increasing the uppertropospheric humidity, and further includes a revision of the turbulent diffusion scheme which reduces turbulent diffusion above the boundary-layer and in stable layers, therefore increasing the wind-shear. Finally, the 32R3 analysis was improved through the introduction of a new radiosonde temperature and humidity bias correction (which reduced the strong daytime low-level dry bias over orography apparent in the analysis of earlier cycles).

As we are primarily concerned with precipitation prediction, the data used in this study are 6-hourly stage-IV accumulated precipitation for North America, and 24-hourly accumulated precipitation from the MAP special observing period. The stage-IV data was obtained for the period 3-16 July 2007, and the MAP data for the period 7 September to 6 October, 1999. The observing periods are spanned by +42 to +66 h IFS T799 91 level forecasts, initialized daily at 00 UTC for the period 1-14 July 2007, and 12 UTC for the period 5 September to 4 October, 1999. Cycles 30R1 and 32R3 were initialised by 32R2 and 32R3 analysis, respectively, for the period 1-14 July 2007. 32R2 was the operational analysis for this period. However, the combination of 32R3 model and 32R3 analysis would best represent the performance of 32R3 operational forecasts. Both cycles were initialised by 21R2 analysis for the period 5 September to 4 October, 1999. 21R2 was the operational analysis for this period. Additionally, to assess the mid-afternoon cloud systems over the Rockies and Great Plains the observed and corresponding forecasted synthetic infrared Brightness Temperatures (BTs) in the 10.8 µm near infrared band (in this band BTs are close to the actual cloud top temperatures) from the GOES 12 satellite are compared. GOES 12 has a spatial resolution of around 4 km. All datasets are interpolated or averaged to a 0.5 degree resolution latitude-longitude grid.

# 3. Results

## 3.1 The Rockies

Figure 1 shows a comparison between the observed and forecasted diurnal cycle of precipitation over the Rockies and the Great Plains. The diurnal cycle of precipitation is clearly evident in the observed data and 32R3 forecasts, with both showing the characteristic mid-afternoon (18-00 UTC) maximum in precipitation to the lee of the Rockies, followed by easterly nocturnal (00-06 UTC and 06-12 UTC) propagating convection over the Great Plains. The 32R3 forecasts tend to overestimate the precipitation. Note that 31R1 and 32R2 forecasts also captured the mid-afternoon maximum in precipitation to the lee of the Rockies, but were less successful in capturing the nocturnal propagation relative to 32R3 (not shown). By contrast, 30R1 forecasts produce little precipitation over the Rockies, but a quasi-stationary rain band over the Great Plains.

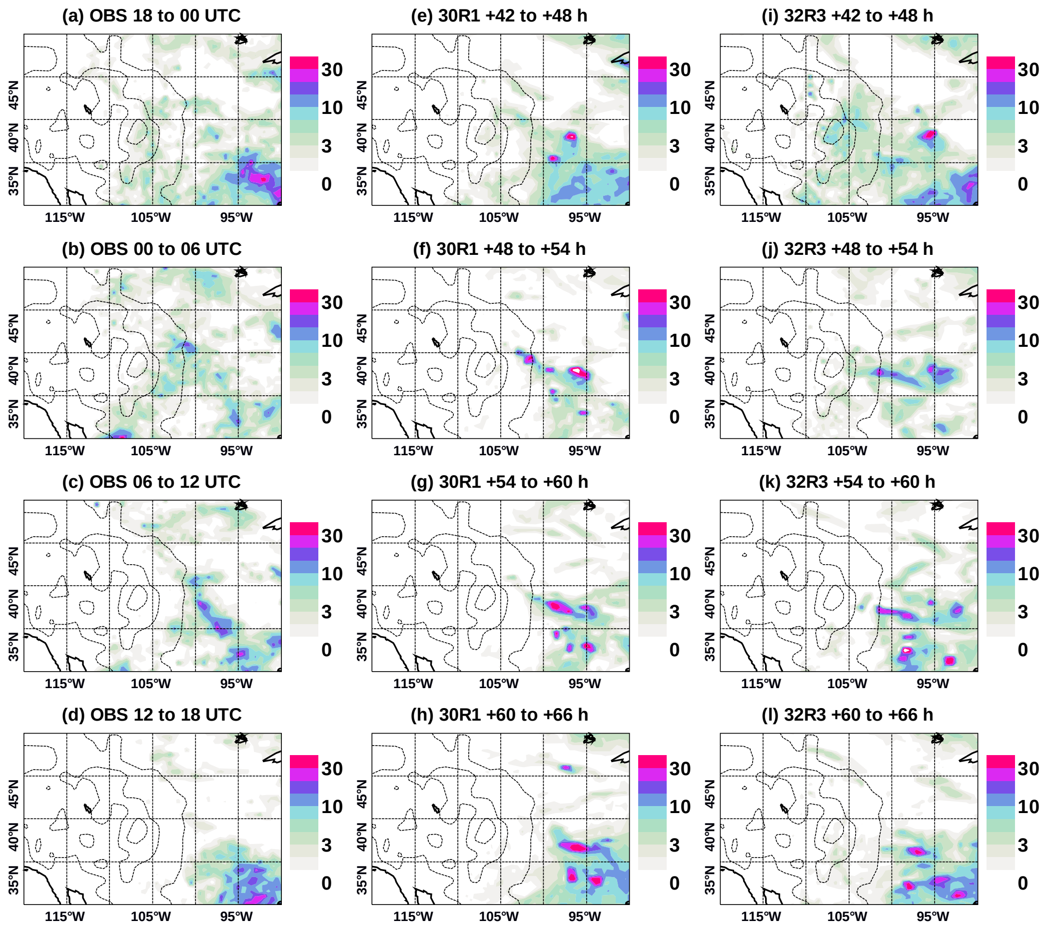


*Figure 1: Composite diurnal cycle of observed and forecast mean 6-hourly accumulated precipitation (mm/day) over the Rocky Mountains and the Great Plains for the period 3-16 July 2007. All times are in UTC (local time is approximately 6 hours behind). Mean stage-IV data (a) - (d), and mean T799L91 +42 to +66 h forecasts initiated at 00 UTC for each day of 1-14 July 2007 with cycle 30R1 (e)-(h), and cycle 32R3 (i)-(l). Dashed contours correspond to the T799 orography height with a 1000 m contour interval.*

Figure 2 shows a time-longitude Hovmöller diagram comparing the observed and forecasted meridionally averaged precipitation. Easterly nocturnal propagation (i.e. 'rain-streaks' that are initiated west of 102°W) is confirmed in both the observations and 32R3. In contrast, 30R1 misses the weaker, propagating convective events, but overestimates the rainfall to the east of the Rockies during the intense precipitation events. Separating the propagating rainfall into parameterized (i.e. convective) and resolved (i.e. large-scale) components (Figure 3) shows that the resolved precipitation dominates, but that the convective contribution increases from 30R1 to 32R3.

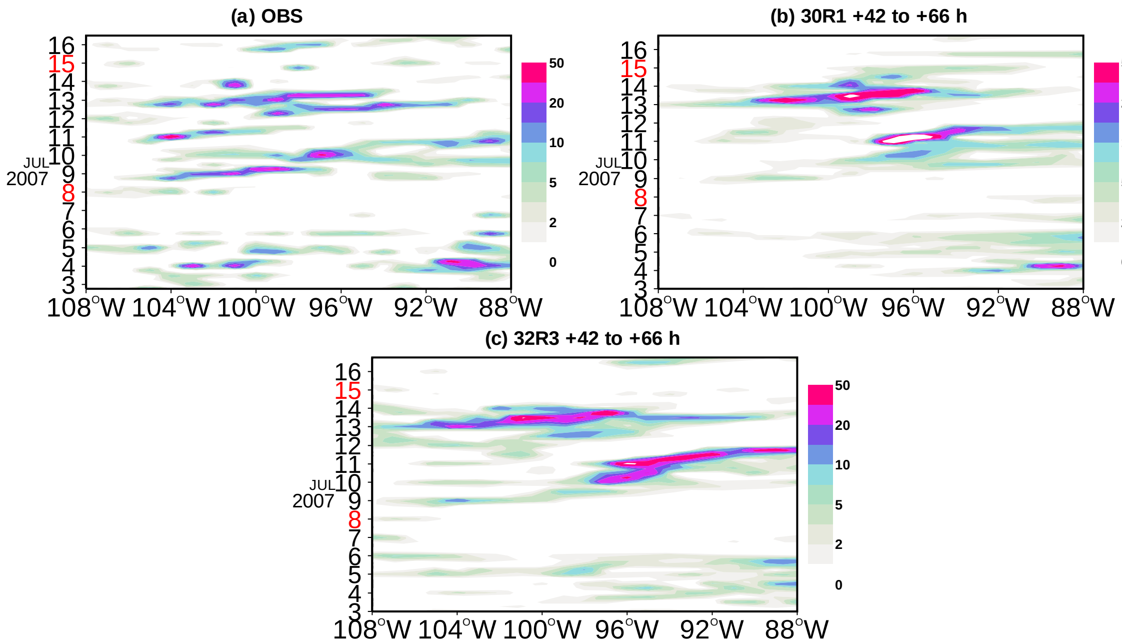


*Figure 2: Time-longitude diagram of meridionally averaged (35 to 45 ° N) 6-h accumulated precipitation (mm/day), stretching from the Rocky Mountains over the Great Plains for the period 3-16 July 2007. Time corresponds to UTC (local time is approximately 6 hours behind). Stage-IV data (a), and daily T799L91 +42 to +66 h forecasts initiated at 00 UTC with cycle 30R1 (b), and 32R3 (c).*

Figure 4 shows a comparison between the observed and synthetic mean BTs over the Rockies and the Great Plains for the period 3-17 July 2007. The observations show minimum temperatures (i.e. high cloud tops) of 250-260 K over much of the Rockies, consistent with the maximum in precipitation around this time. This is broadly captured by the 32R3 forecasts, although the spatial extent is somewhat underestimated. By contrast, the 30R1 forecasts overestimate the temperature by around 20 K, consistent with an underestimation of the depth, duration and horizontal extent of convection. A further quantitative day by day comparison between observed and synthetic BTs based on the mean error averaged over the domain 30 to 50°N and 90 to 120°W is given in Figure 5. Roughly, 32R3 reduces on a day by day basis by 5 K the 9 K warm bias that is present in 30R1, indicating an improvement in the representation of the amount and height of the convective clouds.

Figure 6 compares forecast and (32R3) analysis difference fields of wind, specific humidity, and potential temperature along a vertical transect incident to the Rockies and along 40°N. The 00 UTC fields shows that the strong afternoon moist bias at high levels that is apparent in 30R1 is much reduced in 32R3. Similarly, the warm/dry bias above the lower slopes that is apparent in 30R1 is reduced in 32R3. However, 30R1 forecasts show a small localised cold bias above the upper slopes, which in 32R3 has grown in both spatial extent and magnitude. The reduced wind bias at near-surface level in 32R3 indicates that it better captures the localised upslope winds at this time (Toth and Johnson 1985).

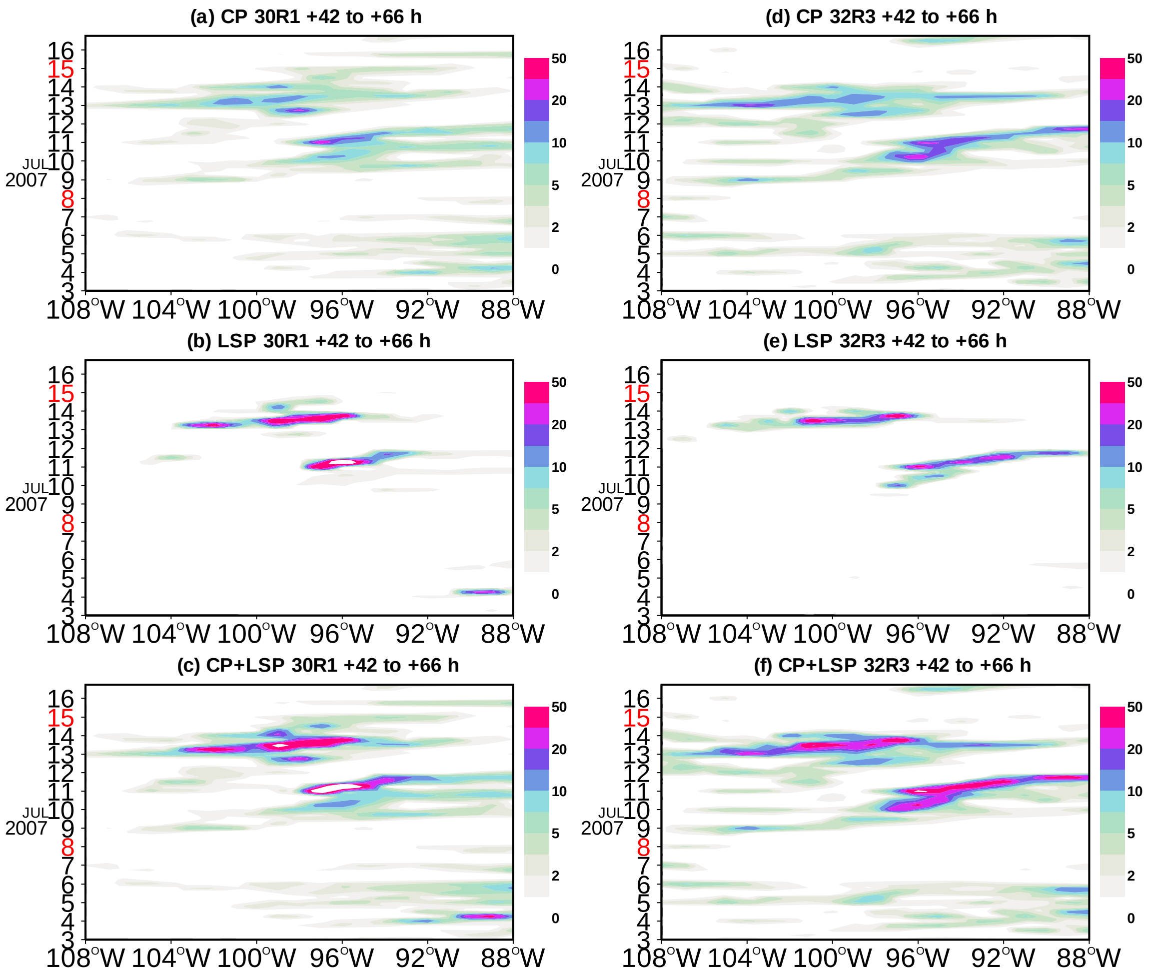


*Figure 3: Time-longitude diagram of meridionally averaged (35 to 45° N) 6-h accumulated 30R1 (a-c) and 32R3 (d-f) +42 to +66 h convective (CP), large-scale (LSP) and total (CP+LSP) precipitation (mm/day), stretching from the Rocky Mountains over the Great Plains for the period 3-16 July 2007.*

Similarly, 32R3 better captures the 06 UTC flow regime in which downslope winds dominate (Toth and Johnson 1985). However, both cycles are characterised by a similar warm/dry bias at low level, and a warm/moist bias at upper level. Above the upper slope, the near-surface cold bias at and the upper level moist bias are reduced in 32R3, perhaps in response to the reduction in wind bias, resulting in (improved) moisture transport. The 12 UTC fields show that 32R3 causes an increase in the upper level warm/dry bias and a decrease in the near-surface moist bias above high slopes. The flow regime is again dominated by downslope winds. Wind biases are reduced during 32R3 forecasts. The resulting (improved) moisture transport producing the reduction in the moist bias above the upper slopes. At 18 UTC the flow regime is characterised by upslope winds, but the circulation is too strong in 30R1, resulting in a warm/dry bias above the lower slopes and a warm/moist bias above the upper slopes. The dry bias is significantly reduced during 32R3, in conjunction with a marked reduction in the wind bias, particularly at near-surface level. However, 32R3 caused an increase in the upper level warm bias.

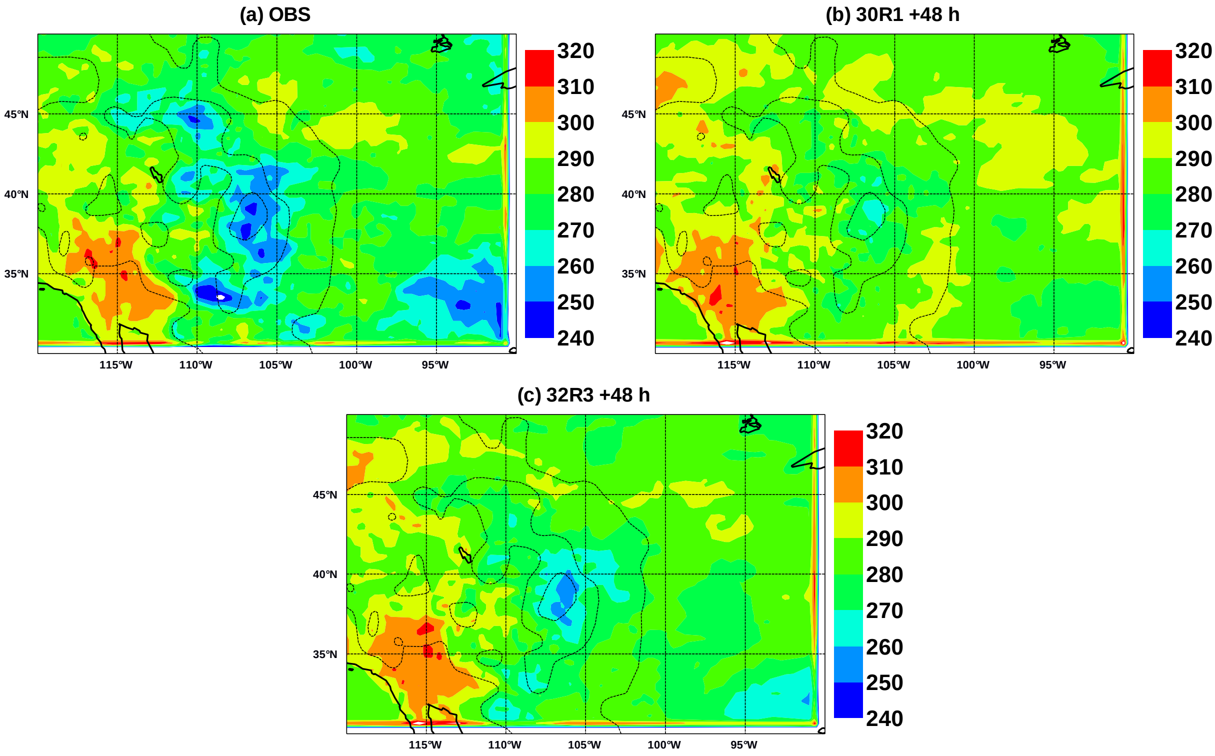


*Figure 4: Composite observed and forecasted synthetic mean 00 UTC infrared BTs (K) at 10.8 µm over the Rocky Mountains and the Great Plains for the period 3-15 July 2007. Mean GOES 12 observations (a), and mean T799 L91 +48 h forecasts initiated at 00 UTC for each day of 1-13 July 2007 with cycle 30R1 (b) and 32R3 (c). Dashed contours denote the T799 orography height with a 1000 m contour interval.*

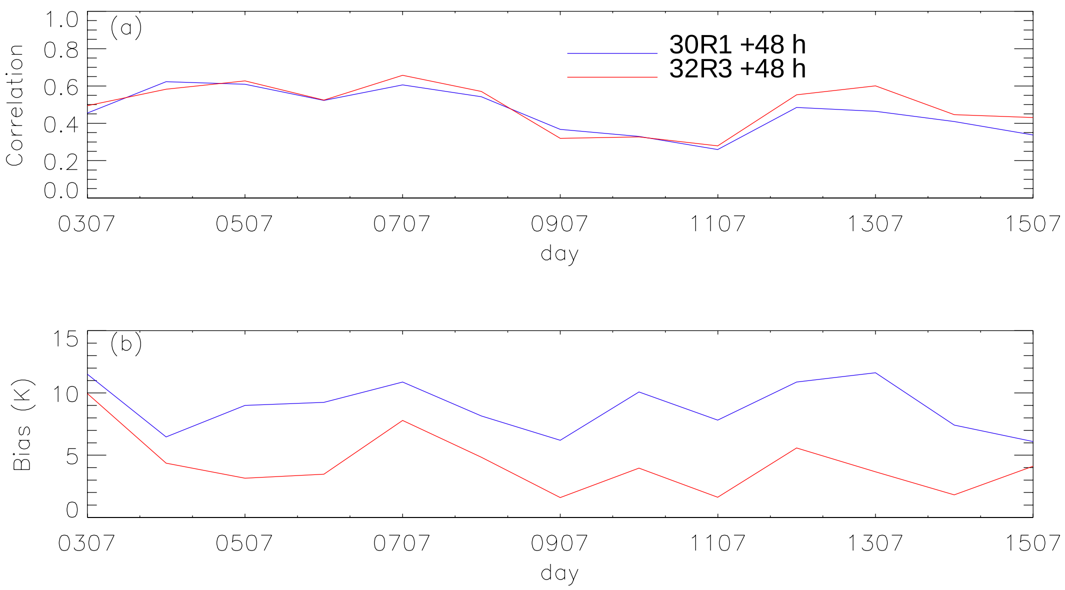


*Figure 5: Time series from 3-15 July 2007 of (a) correlation (b) and bias (K) (averaged over the area shown in Fig. 3) of forecasted synthetic 10.8 µm BT's from T799L91 +48 h forecasts initiated at 00 UTC for each day of 1-13 July 2007 with cycle 30R1 and 32R3 against GOES 12 observations.*

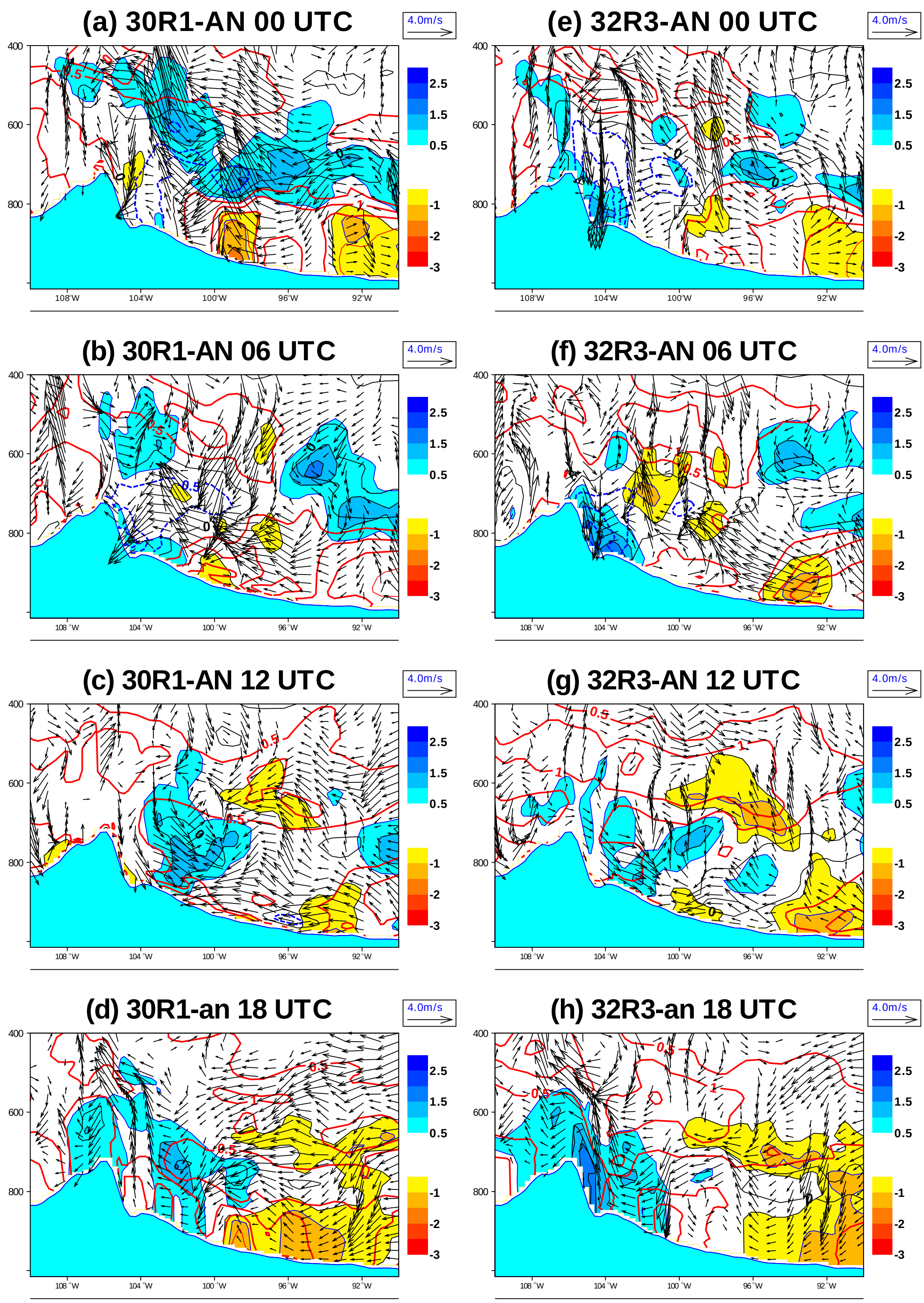


*Figure 6: Composite vertical transects of the diurnal cycle of mean forecast - analysis difference fields of velocity (vectors; ms$^{-1}$) and specific humidity (shading, g kg$^{-1}$), and potential temperature (contours) for the period 3-16 July 2007. Transect is incident to the Rocky Mountains at 40°N, and runs from (right to left) 90 to 110°W. All times are in UTC. (a)-(d) correspond to T799L91 +48 to +66 h forecasts initiated at 00 UTC for each day of 1-14 July 2007 with cycle 30R1, and (e)-(h) to 32R3 forecasts. The reference analysis is the 32R3 analysis.*

### 3.2 The Alps

Figure 7 shows a comparison between the observed and forecasted precipitation over the Alps. The observations show a localised region of maximum precipitation along the southern side of the Alps, consistent with the precipitation climatology of Frei and Schär (1998), and the fact that during September heavy rain is produced through strong large-scale synoptic forcing with the mean flow advecting moisture from the Mediterranean (Keil and Cardinali, 2004). Generally, this region of precipitation is overestimated at the +42 to +66 h forecast range with both 30R1 and 32R3. In particular, they both show a precipitation maximum to the eastern side of the Alps which is not observed, and both overestimate the precipitation over the mountain ranges bordering the Mediterranean.

The overestimation in precipitation was particularly evident in the 32R3 forecast. Separating the forecasts into convective and large-scale precipitation contributions (Figure 8) showed that this was due to an increase in convective precipitation in the 32R3 forecast. Figures 9(a) and 9(b) confirm that both model cycles overestimate the precipitation over the Alpine region, and in particular heavy precipitation. Figure 9(c) shows that the model cycles overestimate precipitation for values larger than 10 mm/day.

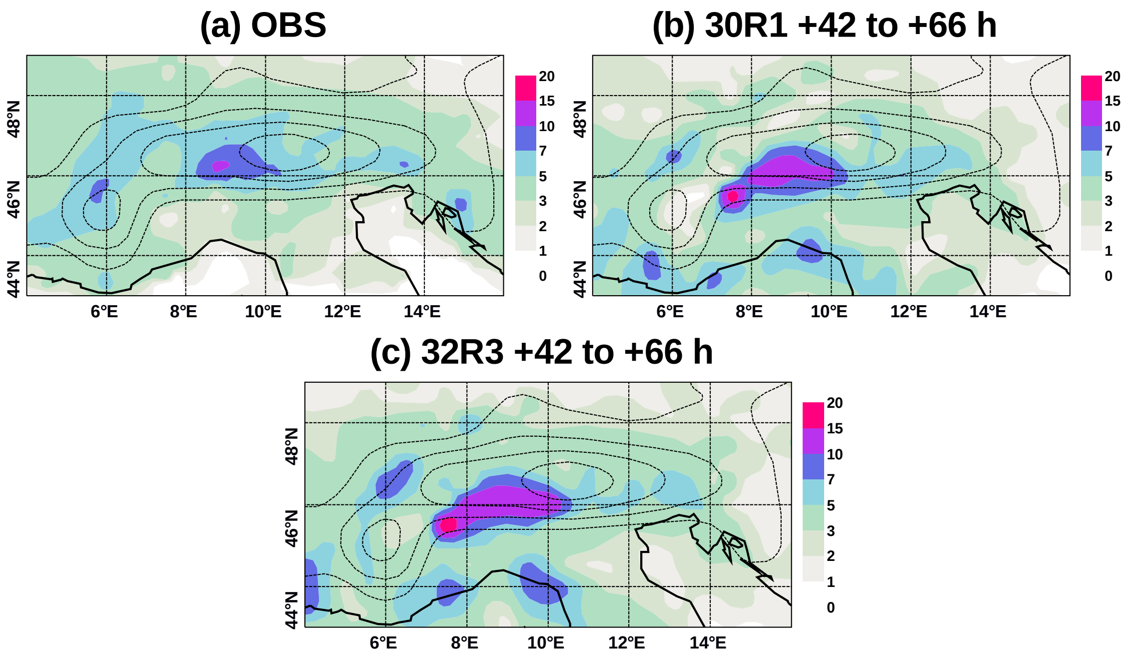


*Figure 7: Composite observed and forecasted mean daily accumulated precipitation (06-06 UTC, mm/day) over the Alps for the period 7 September to 6 October, 1999. Rain gauge data taken during MAP (a), and mean T799L91 +42 to +66 h forecasts initiated at 12 UTC for each day of 5 September to 4 October, 1999 with cycle 30R1 (b) and cycle 32R3 (c). Dashed contours denote the T799 orography height with a 500 m contour interval.*

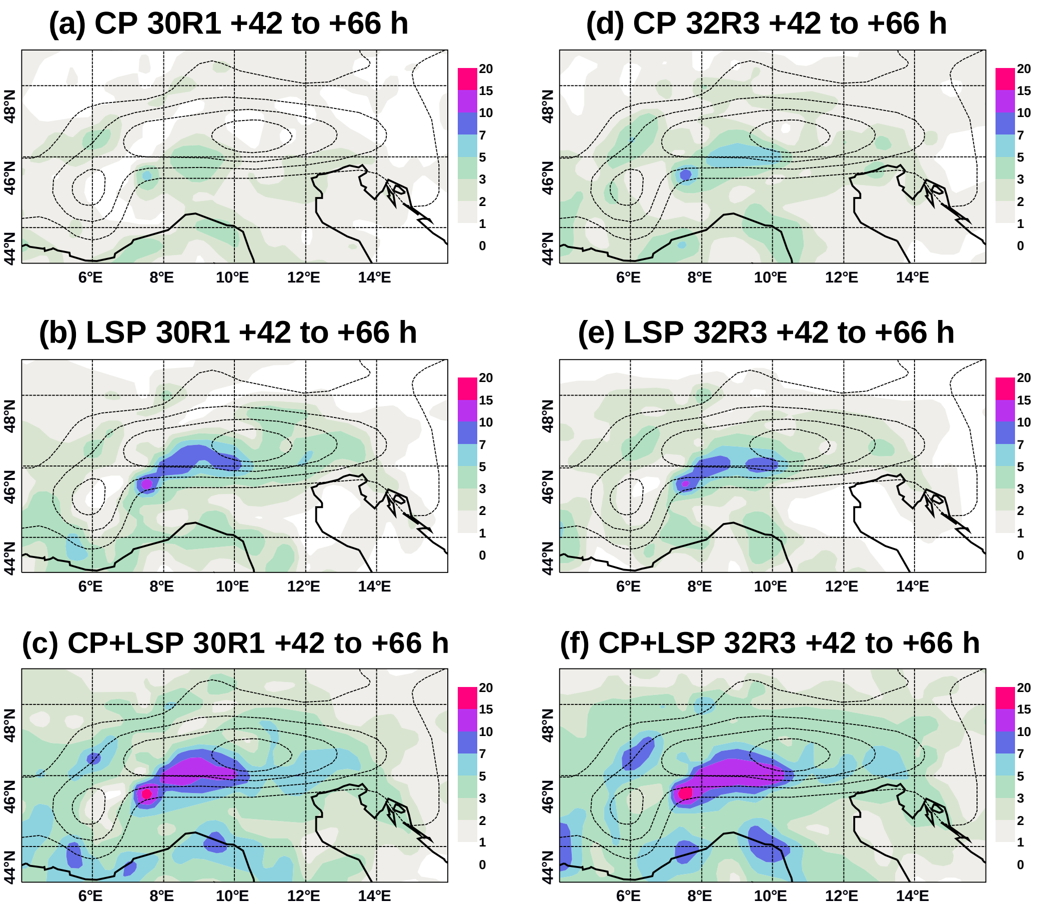


*Figure 8: Composite forecasted mean convective (CP), large scale (LSP) and total (CP+LSP) daily accumulated precipitation (06-06 UTC, mm/day) over the Alps for the period 7 September to 6 October, 1999. Mean T799L91 +42 to +66 h forecasts initiated at 12 UTC for each day of 5 September to 4 October, 1999 with cycle 30R1 (a-c) and cycle 32R3 (d-f).*

# 4. Summary

Revisions to the parameterizations of convection, radiation, diffusion and ice microphysics in the ECMWF model have resulted in a significant improvement in the forecasting of warm season precipitation over the Rockies. Previously, only little precipitation was forecast here, even at a horizontal resolution of 25 km, despite the observations showing a strong diurnal cycle with a mid-afternoon maximum. Moreover, the realistic nocturnal propagation of convective systems over the Great Plains for distances in excess of 1000 km was not captured. However, with model cycle 32R3 the location and timing of the initiation and nocturnal propagation of the convection is improved, but the precipitation amounts are now somewhat overestimated. Furthermore, the biases in wind and moisture are reduced, which is a direct consequence of the improved physics package and, more importantly, an indirect effect of the better representation of mid-tropospheric convective heating (with the associated compensating environmental subsidence) and its interaction with the large-scale flow, in particular the low-level moisture convergence. The new convection formulation is sensitive to the environmental mid-tropospheric humidity and uses a variable adjustment time-scale. This proves crucial in capturing the interaction between convection and the large-scale flow in relatively dry and weakly forced situations where convection both responds to and drives a large-scale circulation.

However, examination of the model cycles between 30R1 and 32R3 (not shown) showed that an improvement in the capture of the mid-afternoon maximum in precipitation was also apparent in 31R1 and 32R2 forecasts. Similarly, 31R1 and 32R2 forecasts demonstrated a reduction in 00 UTC brightness temperature bias over the Rocky Mountains and Great Plains, which is related to improved capture of the mid-afternoon convective cloud. Both these cycles also showed the same reduction in daytime upper level moist bias apparent in 32R3. This suggests that the physics changes such as the treatment of ice supersaturation (in 31R1) and the McRad radiation scheme (in 32R2) directly contributed to the improvement evident in 32R3 forecasts. Moreover, at 12 and 18 UTC the increase in 32R3 upper level warm bias was not apparent in 31R1 and 32R2 forecasts. By contrast, 31R1 and 32R2 failed to capture an improvement in nocturnal propagation, indicating that this improvement was due to the reduction in coupling between deep convection and the large-scale flow introduced in 32R3.

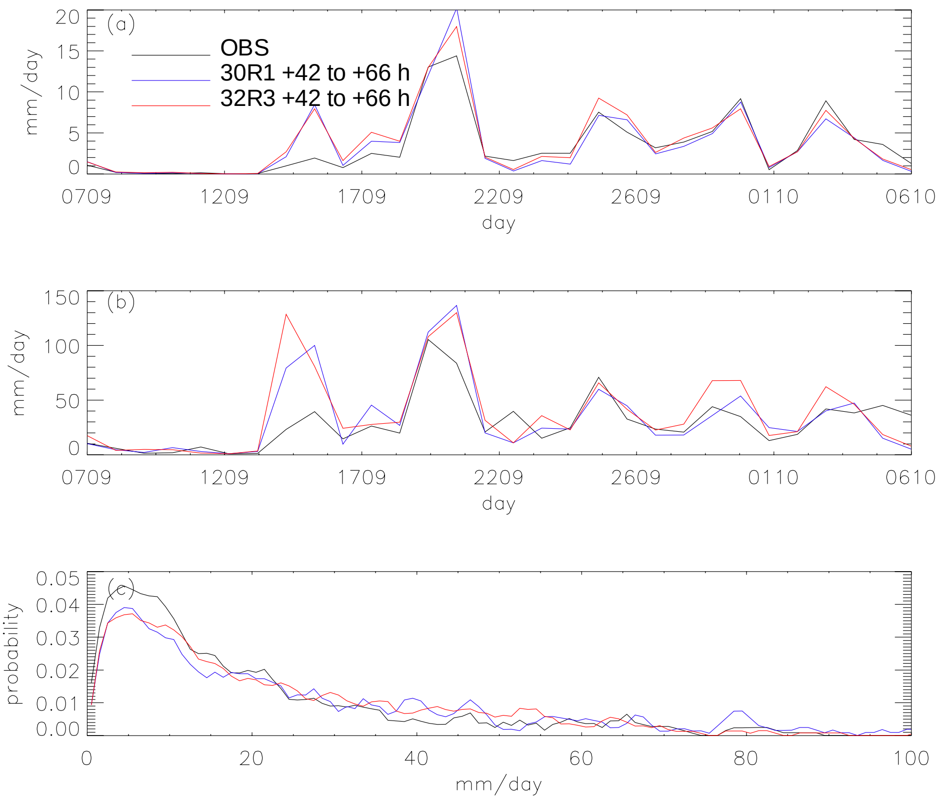


*Figure 9: Time series for the period 7 September to 6 October, 1999 of observed and forecasted (a) mean and (b) maximum daily accumulated precipitation (06-06 UTC, mm/day) over the Alps. (c) Probability distribution function (PDF) of observed and forecasted daily accumulated precipitation rate (06-06 UTC, mm/day) over the Alps for the period 7 September to 6 October, 1999. Rain gauge data taken during MAP (OBS), and T799L91 +42 to +66 h forecasts initiated at 12 UTC for each day of 5 September to 4 October, 1999 with cycle 30R1 and 32R3.*

Moreover, relative to operational analysis a low-level dry bias was apparent in 30R1, 31R1, 32R2, and 32R3 forecasts (not shown). Relative to its own analysis it was shown that 32R3 was responsible for a reduction in this bias, suggesting that the improvement is mainly due to the new radiosonde temperature and humidity bias correction apparent in the 32R3 analysis.

By contrast, over the Alps during the MAP period, both model cycles, and particularly 32R3, overestimated the mean precipitation. This was shown to be through overestimation of precipitation for values larger than 10 mm/day (a bias also evident in earlier model versions). The meteorology of the Alpine region during September is dominated by strong synoptic south south-westerly flow which advects moisture from the nearby Mediterranean which rains over the mountains (which act as a barrier). Therefore, a good representation of the interaction (balance) between the convection and the large-scale flow, as well as a low-level flow over orography via the parameterisation of diffusion and low-level blocking by sub-grid scale orography, is necessary to realistically reproduce the observed precipitation over the Alps. Moreover, the mean forecasted precipitation from both cycles consisted significantly of large-scale precipitation (not shown), suggesting that the overestimate of mean precipitation is related to excessive low-level blocking. This conclusion is consistent with the results of Keil and Cardinali (2004), which discussed the forecasting of IOP2b and IOP8, which are characterised by unblocked/flow-over and blocked flow regimes respectively. For IOP2b their MAP-RA results showed an underestimation of precipitation over the Alps, while for IOP8 their results suggested an overestimation over its western and eastern sides. Both these results are consistent with excessive low-level blocking.

However, the largest impact globally of the model changes presented was not on midlatitude precipitation (convective systems associated to synoptic disturbances) but on tropical convective systems over Africa and South America, where the accurate coupling of the large-scale dynamics and the model physics becomes important in successfully simulating the phase and amplitude of convectively coupled waves (Bechtold et al. 2008).

### Acknowledgments

The authors are grateful to the two anonymous reviewers, whose comments and suggestions improved the manuscript submitted to *Meteorology and Atmospheric Physics*. Many thanks to Fernando Li for his help with the plotting software, and Carole Peubey for help computing the simulated brightness temperatures, and to Anton Beljaars for reading a early version of the memo.

### References

Banta, R. M., and Hanson, K. R., ‘Numerical simulations of the development of mountain cumulus clouds’, Short and medium-range numerical weather prediction, Matsuno, T., Ed., Meteor. Soc. Japan, Tokyo, 767-775, 1987.

Bechtold, P., Chaboureau, J. P., Beljaars, A., Betts, A. K., Köhler, M., Miller, M., and Redelsperger J. L., ‘The simulation of the diurnal cycle of convective precipitation over land in a global model’, *Q. J. R. Meteorol. Soc.*, **130**, 3119-3137, 2004.

Bechtold, P., Köhler, M., Jung, T., Leutbecher, M., Rodwell, M., and Vitart, F., ‘Advances in simulating atmospheric variability with IFS cycle 32r3’, ECMWF Newsletter, No. 114, 29-38, 2008.

Bougeault, P., and others, ‘The MAP Special Observing Period’, *Bull. Am. Meteorol. Soc.*, **82**, 433-462, 2001.

Carbone, R. E., Tuttle, J. D., Ahijevych, A., and Trier, S. B., ‘Inferences of predictability associated with warm season precipitation episodes’, *J. Atmos. Sci.*, **59**, 2033-2056, 2002.

Cheinet, S., Beljaars, A., Köhler, M., Morcrette, J.-J., and Viterbo, P., ‘Assessing physical processes in the ECMWF model forecasts using ARM SGP observations’, ECMWF ARM Report Series No. 1, 2005.

Cherubini, T., Ghelli, A., and Lalaurette, F., ‘Verification of precipitation forecasts over the Alpine region using a high density observing network’, ECMWF Technical Memorandum, No. 340, 2001.

Davis, C. A., Manning, K. W., Carbone, R. E., Trier, S. B., and Tuttle, J. D., ‘Coherence of warm-season continental rainfall in numerical weather prediction models’, *Mon. Wea. Rev.*, **131**, 2667-2679, 2003.

Frei, C., and Schär, C., ‘A precipitation climatology of the Alps from high-resolution rain-gauge observations’, *Int. J. Climatol.*, **18**, 873-900, 1998.

Keil, C., and Cardinali, C., ‘The ECMWF reanalysis of the MAP special observing period’, *Q. J. R. Meteorol. Soc.*, **130**, 2827-2849, 2004.

Morcrette, J.-J., and others, ‘Recent advances in radiation transfer parameterizations’, ECMWF Technical Memorandum, No. 539, 2007.

Olson, D. A., Junker, N. W., and Korty, B., ‘Evaluation of 33 years of quantitative precipitation forecasting at the NMC’, *Wea. Forecasting*, **10**, 498-511, 1995.

Pedemonte, L., Corazza, M., Sacchetti, D., Trovatore, E, and Buzzi, A. ‘Verification of limited-area model precipitation forecasts during the MAP-SOP’, Extended abstract for International Conference on Alpine Meteorology (ICAM), 2005.

Tiedtke, M., ‘A comprehensive mass flux scheme for cumulus parameterization in large-scale models’, *Mon. Wea. Rev.*, **117**, 1779-1800, 1989.

Toth, J. T., and Johnson, R. H., ‘Summer surface flow characteristics over northeast Colorado’, *Mon. Wea. Rev.*, **113**, 1458-1469, 1985.

Wallace, J. M., ‘Diurnal variations in precipitation and thunderstorm frequency over the conterminous United States’, *Mon. Wea. Rev.*, **103**, 406-419, 1975.