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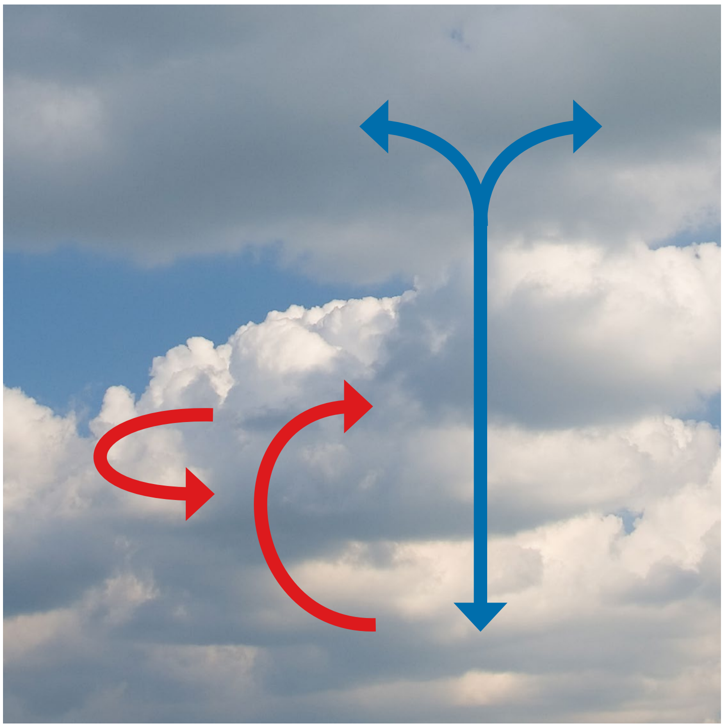

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A major moist physics upgrade for the IFS

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After nearly five years of development, we are in the final stages of refinements and verification of major changes to the moist physics intended for implementation in the next upgrade of ECMWF's Integrated Forecasting System (IFS Cycle 48r1).

One of the main drivers of this project was ECMWF's strategic decision to move towards an ensemble forecast horizontal grid spacing of about 5 km, down from 18 km today. With this in mind, the project aimed to revise the moist physics to ensure that the complicated interactions between turbulence in the lowest part of the atmosphere, convective motions and the cloud physics are described as simply, efficiently, accurately and scale-independently as possible. These developments make it possible for the IFS to be run across a broader range of horizontal resolutions, including convection-permitting resolutions.

A second motivation for the moist physics upgrade was to tackle longstanding systematic model errors in clouds, precipitation and radiation across all resolutions and forecast lead times. Due to the sensitivity of the forecast to moist processes, the complex nature of atmospheric interactions, and compensating errors in the model, there is an increasing need to implement targeted combinations of physics changes together to address systematic errors in a more holistic way.

The upgrade brings a significantly improved physical basis for moist processes and is necessary to facilitate future development of the IFS. Here we give a short overview of changes in the representation of turbulence, clouds, and shallow and deep convection, with a focus on some of the main impacts of the upgrade. A more quantitative assessment of the impact of these changes on the overall performance of the forecasting system will be reported once IFS Cycle 48r1 has been implemented.

Parametrizing moist processes in the IFS

Moist processes in the IFS are represented with physically based parametrizations for turbulent mixing, convection, subgrid clouds and microphysics. Each parametrization is called sequentially during every model time step. Although parametrizations are often developed as separate entities, it is vital that they interact with each other in a physically consistent way to represent real-world processes effectively. There are therefore many dependencies between schemes. Individual developments over many years have led to some complications and inconsistencies in the way these schemes work together. For example, in the layer of the atmosphere most directly affected by surface heating and friction (the boundary layer), there are inconsistencies between the buoyant updraughts used in the turbulence and convection schemes. In addition, the separate cloud saturation adjustments in the turbulent mixing scheme often conflict with the main cloud scheme and there are multiple saturation adjustment steps throughout the timestep. These inconsistencies have been resolved in the moist physics upgrade (Figure 1).

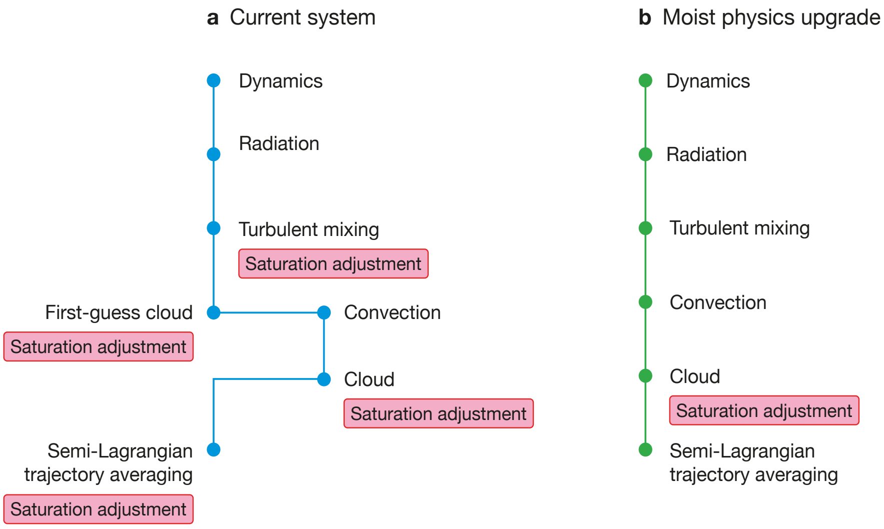

Figure 1 IFS physics parametrization call sequence, highlighting the differences in saturation adjustment between (a) moist physics in the current IFS and (b) the moist physics upgrade planned for IFS Cycle 48r1. In (a), half the temperature and humidity tendencies from the first-guess call to the cloud scheme are added to the state seen by the main convection and cloud schemes.

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The convective boundary layer

In the IFS, the mixing in the convective boundary layer is represented by two schemes: a turbulence scheme (Köhler et al., 2011) and a moist convection scheme (Bechtold et al., 2014). The turbulence scheme comprises a turbulent eddy diffusion and mass flux scheme, which represents clear and stratocumulus-topped boundary layers. The moist convection scheme comprises a mass flux scheme for moist shallow and deep cumulus convection.

An important quantity in the turbulence scheme is the eddy diffusion coefficient K, which is computed using a K-profile closure. The scaling of the diffusion coefficients and the height to which diffusive mixing is applied depends on the mixed layer height. The latter is currently computed inside the turbulence scheme from a convective updraught model that is different from that used in the moist convection scheme. This convective updraught model is also used to diagnose if the boundary layer is clear or cloudy and to detect the cloud base. A distinction is made between a cumulus (Cu) and stratocumulus (Sc) topped boundary layer based on the inversion strength. For Sc cases, the moist convection scheme is switched off. The mixed layer height is equal to the boundary layer height for clear and Sc cases and to cloud base for Cu cases. Entrainment mixing is applied for all boundary layers, with an extra mixing term proportional to the radiative cooling at cloud top in Sc cases. The turbulent mass flux is only applied in clear boundary layers.

Clouds are represented by a separate cloud scheme (Tiedtke, 1993). In this scheme, detrainment from the moist convection scheme is an important source term. In addition, in an Sc-topped boundary layer, clouds are generated by a statistical subgrid condensation scheme that is embedded in the turbulent diffusion scheme.

The code structure and interactions between these three schemes has become complicated over time, leading to inconsistencies in physical assumptions. For example, the updraught model in the turbulence scheme estimates a much lower occurrence of Cu cases than the moist convection scheme. More importantly, there is no clear separation between processes, such as the dry and moist convective and turbulent mixing and the respective sources in the turbulence scheme on the one hand and the moist convection scheme on the other. We therefore decided to radically simplify the overall code structure and the turbulence scheme code in particular. The aim was to formulate consistent interactions between the schemes across all types of convective boundary layers, as indicated in the schematic in Figure 2.

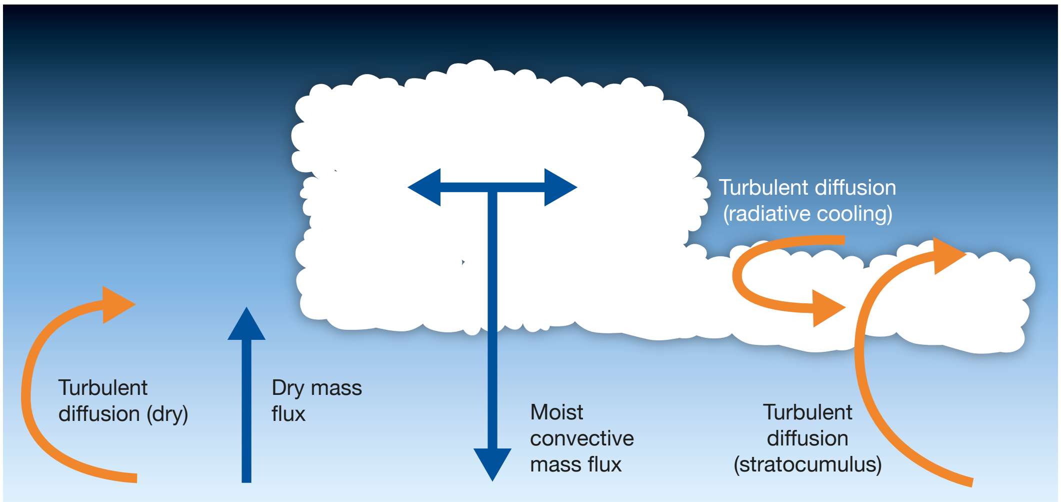

Figure 2 Schematic of the representation of the cloudy convective boundary layer in the IFS, consisting of moist convective mass flux in the moist convection scheme and dry mass flux and turbulent diffusion in the turbulence scheme. The turbulent diffusion coefficient K has a quasi-dry K-profile in a clear-sky boundary layer. In the presence of stratocumulus clouds, the K-profile Sc extends to the cloud top and contains an additional contribution from radiative cooling and cloud top entrainment.

The main scientific formulation of the physical processes for the convective boundary layer remains the same as before, but there are several important differences introduced with the moist physics upgrade:

- The mixed layer height up to which the K-profile is applied in the turbulence scheme is now computed using the same updraught model as that used in the moist convection scheme. The mixed layer height is still typically near the inversion top in the clear boundary layer, near the cloud base for Cu-topped boundary layers and near the cloud top for Sc-topped boundary layers.

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- The criterion used to distinguish between Sc and Cu topped boundary layers has been revised by computing the strength of the temperature inversion using a new method, based on the variation of moist entropy (Marquet, 2010).
- At the top of the mixed layer, mixing via cloud top entrainment proportional to 20% of the surface buoyancy flux is applied for all types of boundary layers. In the case of Sc, an additional term is applied to represent radiatively driven entrainment. An increased contribution to turbulent mixing from radiative cooling is still applied in Sc-topped boundary layers.
- The shallow part of the moist convection scheme now does all the moist transport, including in stratocumulus, where it acts together with the radiatively driven turbulent mixing. This made it necessary to improve the numerical stability of the convection scheme as the divergence of the mass flux is large in Sc in the vicinity of inversions. The dry mass flux from the turbulence scheme is now applied only in clear boundary layers.
- The statistical cloud scheme has been removed from the turbulent diffusion scheme and all cloud processes are handled by the cloud scheme.
- The sub-time stepping (iteration) used for many years in the turbulence scheme has been removed, improving the computational efficiency of the IFS whilst maintaining the scheme's good performance.

The upgrade has improved the representation of turbulent and convective mixing in the convective boundary layer in a simple and consistent way that works for clear, cumulus- and stratocumulus-topped boundary layers and their transitions. Figure 3 shows an example of the transition from stratocumulus to cumulus along a section across the Pacific Ocean and highlights the more realistic behaviour of the modelled boundary layer cloud with the moist physics upgrade.

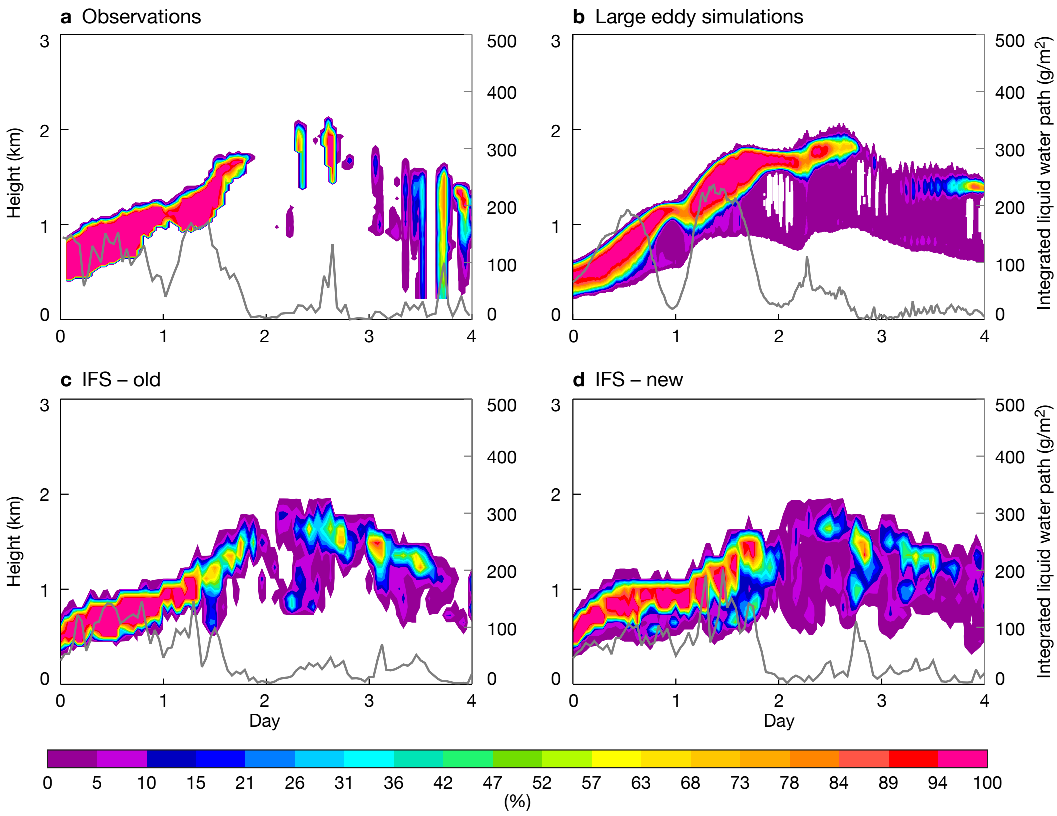

Figure 3 Cross section from the south Californian coast to Hawaii showing the evolution of cloud fraction profiles (shading) and integrated liquid water path (grey lines) from 21 to 25 July 2013 along the ship track of the Marine ARM GPCI Investigation of Clouds (MAGICS) campaign according to (a) instruments onboard the MAGICS ship, (b) large eddy simulations (LES) forced by IFS analyses, (c) re-forecasts starting at 00 UTC on 21 July using IFS Cycle 46r1 and (d) the same re-forecasts with the moist physics upgrade. Note that the radar in (a) has a sensitivity threshold and the plot shows a point profile, while (b), (c) and (d) show area means. This helps to explain the larger gaps in (a) compared to the other plots. The discrete steps in the rising cloud top in the IFS in (c) and (d) are due to the coarser vertical resolution compared to the LES.

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Saturation adjustment and the cloud scheme

The saturation adjustment process calculates the amount of condensation or evaporation due to changes in temperature and humidity in a model grid box. It allows for partially cloudy grid boxes with subsaturation, and for supersaturation (with respect to ice) at temperatures below freezing in the clear air part of the grid box. The cloudy part is always at saturation (liquid or ice, depending on temperature).

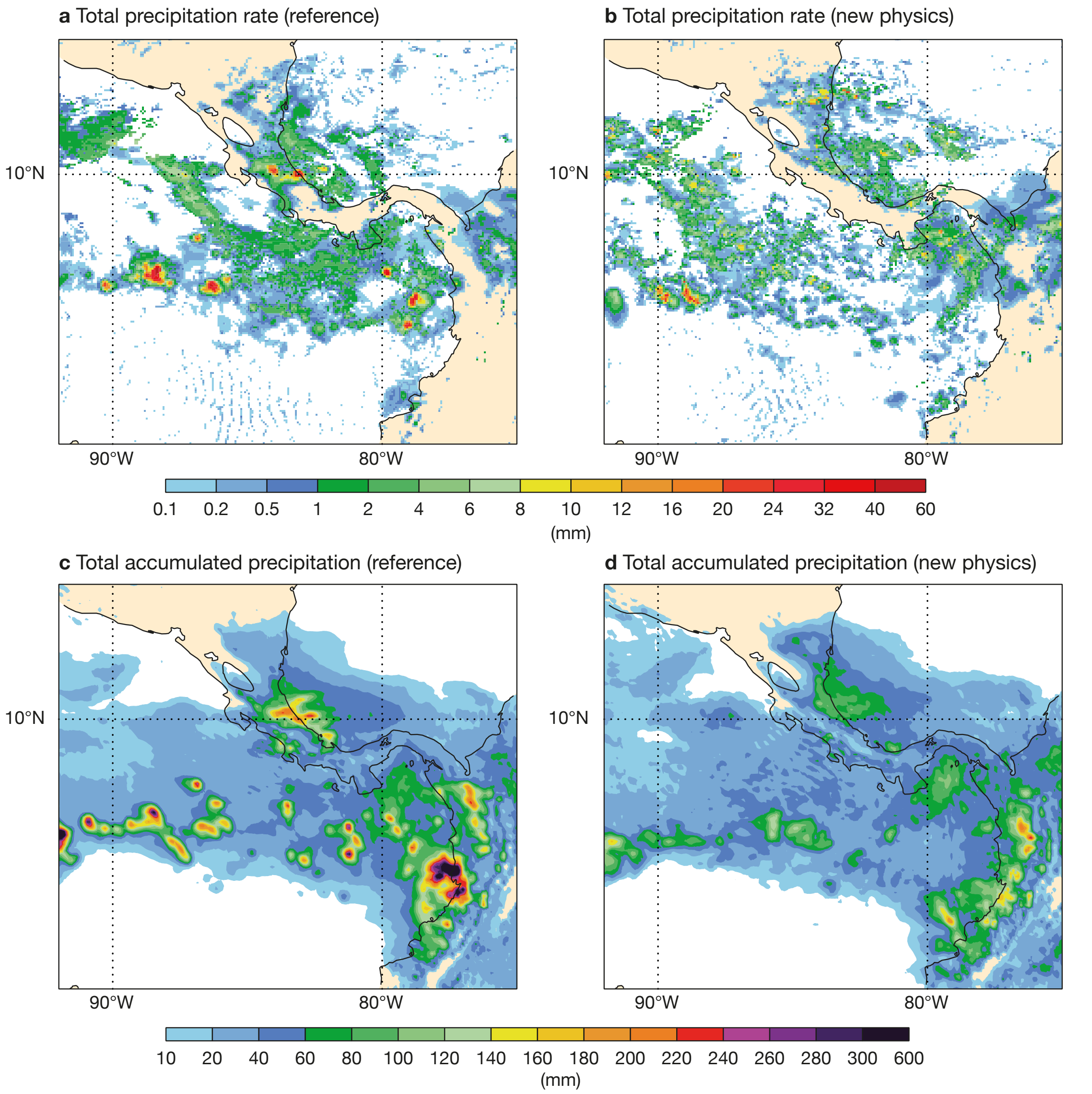
The scheme assumes a simple form of subgrid variability of temperature and humidity to predict how the condensate and cloud fraction change due to various processes including adiabatic cooling, convective subsidence warming, turbulent mixing and microphysics. Saturation adjustment is performed in multiple places in the current IFS code with a different set of assumptions in the turbulence scheme compared to the rest of the model. Saturation adjustment in the IFS is therefore not straightforward and contains several assumptions, thresholds and limiters for numerical stability for long time steps, particularly for the ice phase. Several issues have been identified and are addressed as part of the moist physics upgrade:

- An overly complicated call sequence for cloud and convection processes was obscuring an error in the saturation adjustment to the temperature forcing from the dynamics. This has now been corrected as part of the moist physics upgrade. At the same time, the interactions between the turbulence, moist convection and cloud schemes have been significantly simplified so that saturation adjustment now only takes place in the cloud scheme (Figure 1). Positive impacts include a reduction in the number of overactive quasi-stationary precipitation cells, which have been a longstanding problem in the IFS in the tropics (Figure 4).
- The original saturation adjustment process in the IFS only modified cloud fraction in partially cloudy grid boxes as a result of changes in temperature. It included a separate step to adjust for supersaturation resulting from changes in humidity. This has been modified to take into account changes in temperature and humidity simultaneously. Doing so enables direct input of tendencies from the moist convection and turbulence schemes. As mentioned earlier, the separate cloud scheme within the turbulence scheme has been removed, leading to a simpler and more consistent representation of cloud fraction tendencies across the model.
- For partially cloudy grid boxes, the threshold for maximum ice supersaturation in the clear-sky and the numerical limiter for condensation have both been revised to be more physically meaningful and consistent across processes. This beneficially increases the cloud cover in deep cloud systems and humidity in the mid-to-upper troposphere.
- In the current IFS, the slow physics tendencies are averaged along the semi-Lagrangian trajectory at the end of the time step. As this can introduce unphysical supersaturation due to inconsistencies in the averaged temperature and humidity, there is a final saturation adjustment step to remove any supersaturation. However, in practice this final adjustment step also removes a significant proportion of the supersaturation that should have been removed earlier by the cloud scheme. With the improved treatment of the saturation adjustment in the moist physics upgrade, these final tendencies now become small. This impacts the ensemble perturbations as more of the condensation warming due to the removal of supersaturation is done in the part of the tendencies that are included in the Stochastically Perturbed Parametrization Tendencies (SPPT) scheme. The result is a welcome increase in the spread of the ensemble in the first few days of the forecast.

Microphysical processes and interaction with radiation

The moist physics upgrade also improves the parametrization of microphysical processes by introducing additional processes for the depositional growth of precipitating snow, the evaporation of cloud ice, and the collision-collection of rain and snow particles. The warm-rain collision–coalescence process (autoconversion–accretion) at supercooled temperatures can now form supercooled rain drops. This will enable the IFS to predict the hazardous precipitation type ‘freezing drizzle’. This is different from the existing precipitation type ‘freezing rain’, which is produced through a different process.

Improving the realism of microphysical processes is an important part of reducing compensating errors and systematic errors in the model and improving forecast skill. Even small changes to processes such as the warm-rain formation process, rain evaporation or ice sedimentation can have significant impacts on the cloud and precipitation field and can affect shortwave and longwave radiation. To improve the realism of radiation further, the physics upgrade also includes a change to use the observed exponential–random vertical overlap of subgrid cloud fraction. ‘Exponential’ here refers to the exponential overlap within a cloud layer as a function of layer depth, and ‘random’ to the random overlap between separate cloud layers. This replaces the exponential–exponential cloud overlap scheme currently used in the IFS.



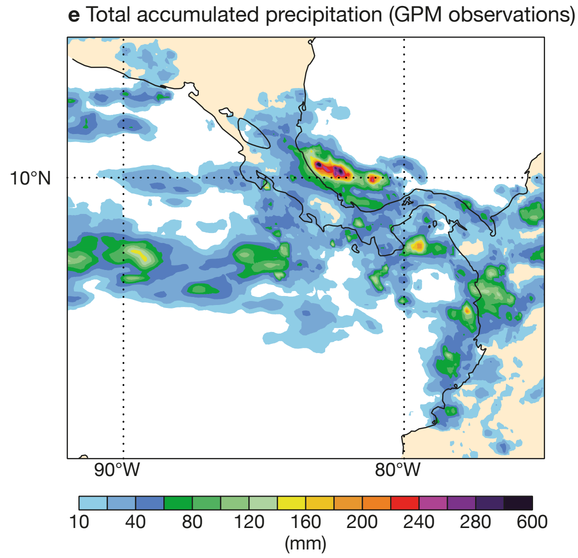


Figure 4 Example of the impact of the moist physics upgrade on total precipitation along the Intertropical Convergence Zone in the eastern Pacific from an HRES forecast (IFS Cycle 47r1) from 00 UTC on 01 July 2019, showing (a) a snapshot of total precipitation rate at 60 hours into the forecast without the new physics ('reference') (b) the same as (a) but with the new physics, (c) total accumulated precipitation from a 72-hour forecast without the new physics ('reference'), (d) the same as (c) but with the new physics, and (e) the 72-hour accumulated precipitation estimate for the same period from the NASA GPM-IMERG3 (version 6) daily rainfall product at 0.1 degree resolution.

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It is important to reduce systematic errors in the model, not only to reduce model bias for the assimilation system, but also for the longer range, as the predicted model state rapidly evolves away from the initial state towards the model's own climate. The combined improvements to the turbulence, convection, cloud and radiation schemes affect many aspects of the forecast and help to reduce some significant systematic errors across forecast lead times. This is particularly true for cloud and its impacts on radiation (Ahlgrimm et al., 2018). As an example, Figure 5 shows how much the moist physics upgrade improves the model climate for global cloud cover and top-of-atmosphere shortwave radiation compared to observations. Although the lack of cloud in the subtropical marine stratocumulus regions has not yet been addressed, elsewhere both cloud and radiation errors have been significantly reduced in most places.

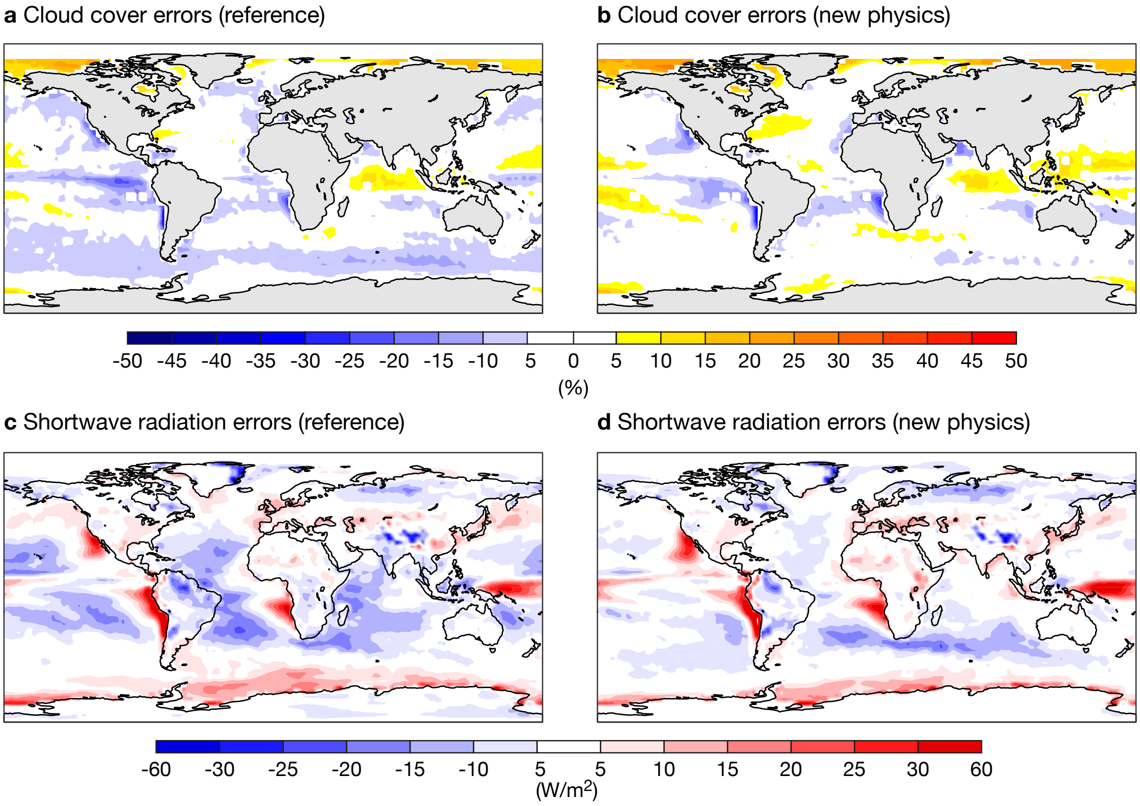

Figure 5 Cloud and radiation evaluation from a small ensemble of 1-year free-running coupled integrations with IFS Cycle 47r1. The charts show (a) the annual mean difference in total cloud cover over open water between the model and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) climatology without the new physics ('reference'), (b) the same as (a) but with the new physics, (c) the annual mean difference in top-of-atmosphere net shortwave radiation between the model and the CERES–EBAF (Clouds and Earth's Radiant Energy System – Energy Balanced and Filled) product without the new physics ('reference') and (d) the same as (c) but with the new physics. Negative (positive) values correspond to excessive (insufficient) outgoing shortwave radiation. Longstanding systematic errors in cloud cover are reduced at the same time as improving the radiation fields.

Deep convection and mesoscale convective systems

The moist physics upgrade also addresses errors in the parametrization of deep convection, especially for the representation of propagating mesoscale convective systems and their diurnal cycle. In particular, insufficient night-time convection over land has been identified as a major shortcoming in IFS forecasts of convective activity.

The issue is illustrated in Figure 6, which shows the evolution of convection on 12 August 2017 at 15, 18 and 21 UTC over Central Africa and the Sahel region. The plots show observations from the 10.8 µm infrared channel of Meteosat-10 (Figure 6a) and 3-hourly rain accumulations from the TRMM radar product 3B42 (Figure 6b). Consistently, these observations show mesoscale convective systems, including some in the band of 10–18°N that intensify during the afternoon and early night-time hours and propagate westward.

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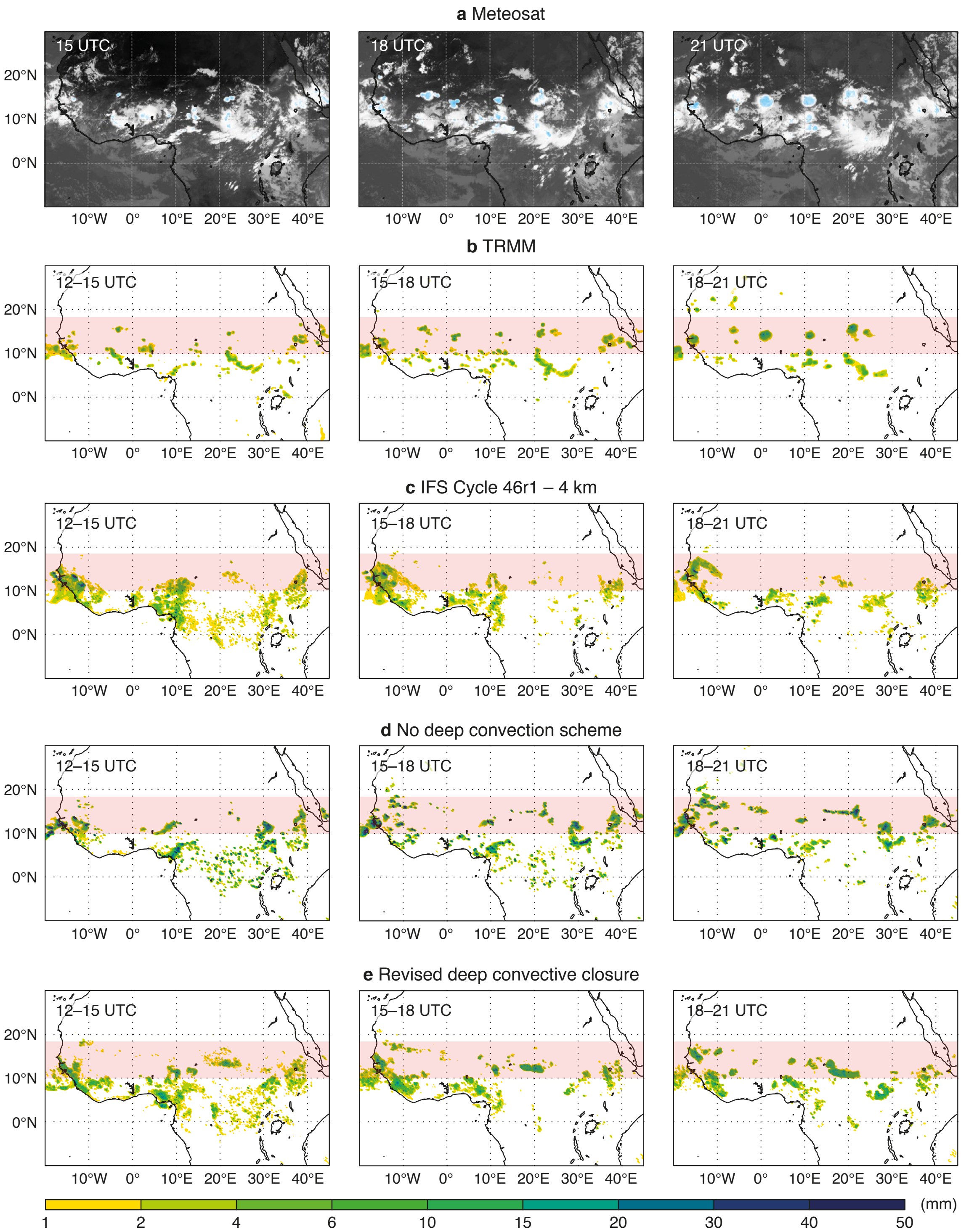

Figure 6 Evolution of continental convective systems over tropical Africa during 12 September 2017 as reflected in (a) Meteosat-11 infrared images at 10.9 µm wavelength at 15, 18 and 21 UTC, and (b) 3-hourly accumulated rainfall (mm) from 12–15, 15–18 and 18–21 UTC according to the TRMM 3B42 observational product. The other panels show the same as (b) but according to (c) 4 km re-forecasts using IFS Cycle 46r1, (d) 4 km IFS re-forecasts without the deep convection scheme, and (e) 4 km IFS re-forecasts with the revised deep convective closure. The IFS re-forecasts start at 00 UTC on 11 September 2017. There is no TRMM 3B42 data east of 29°E at 21 UTC. The evolution of precipitation in the highlighted band from 10–18°N is better reflected in (d) and (e) than in (c).

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To explore the potential of the IFS to adequately represent such processes at future higher resolutions, we have rerun this case with IFS Cycle 46r1 but at 4 km horizontal resolution using the deep convection parametrization (Figure 6c) and without that parametrization (Figure 6d). As developed through a collaboration with Günther Zängl at the German national meteorological service (DWD), the deep convection parametrization includes a smooth reduction of the parametrized convective fluxes, and therefore a transition to resolved convection with increasing resolution (grid spacings smaller than 8 km).

With the deep convection parametrization, the rainfall patterns in Figure 6c are too broad-scale and the night-time propagating systems at 15°N are absent. Similar results are obtained with the operational 9 km grid spacing (not shown). In contrast, without the deep convection parametrization (Figure 6d) the representation of the intense westward-propagating mesoscale systems is improved. However, the amplitude of these systems is too strong, as is evident from a comparison with the TRMM data, and global precipitation is overestimated by more than 10%. Also, the root mean square error of precipitation and upper-air forecast skill are significantly degraded with this version of the model.

We have therefore decided to explore further avenues of improving the convection parametrization. These include the coupling between the convection and the dynamics, which is particularly delicate in the case of mesoscale convective systems that propagate and regenerate by producing their own horizontal convergence. During a research stay of Tobias Becker (Max Planck Institute for Meteorology) at ECMWF, we analysed output from runs without deep convection parametrization over Africa for the whole month of August. It was found that the lack of intense continental convection in the parametrization can be corrected for by including the total advective moisture convergence in the convective instability closure. The results with the revised closure at 4 km are shown in Figure 6e. Using the revised parametrization makes the convection more intense than when using the current scheme, and realistic propagating features develop when compared with the observations in Figure 6b. Overall the results are now somewhere in between the current operational scheme and the simulations without the deep convection parametrization.

The evaluation of the IFS with the revised deep convection, which is part of the moist physics upgrade, is ongoing. The results so far have shown that the revised closure improves rainfall distribution and particularly the prediction of high rainfall rates. It also improves the model variability in the medium and long range. However, it increases root-mean-square precipitation forecast errors by about 1–2% in short-range deterministic high-resolution forecasts. Figure 7 shows an evaluation of the frequency distribution of 48–72 h forecast rainfall totals against radar observations for June 2018 over Europe (OPERA data) and North America (NEXRAD-Stage IV data) using a small ensemble consisting of one unperturbed and eight perturbed members at resolution TCo399 (corresponding to a grid spacing of about 25 km). For both regions a clear underestimation of rainfall intensities >10 mm/24 h is evident in the operational model. The underestimation is alleviated by the revised closure.

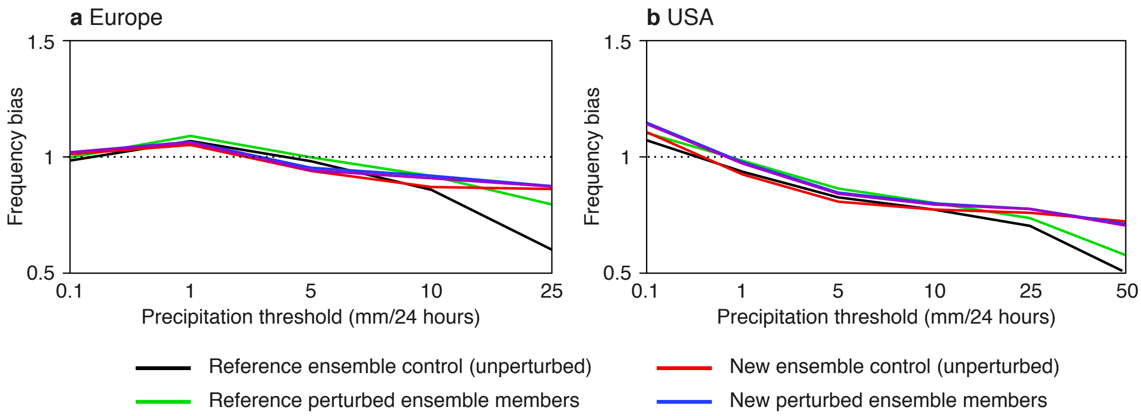

Figure 7 The plots show the frequency bias of 48–72-hour ensemble forecasts of total rainfall during June 2018 for different thresholds of precipitation compared to (a) OPERA radar observations over Europe and (b) NEXRAD-Stage IV radar data over the continental USA. Results are shown for one unperturbed member (Control) and the mean of eight perturbed members (Perturbed) using IFS Cycle 46r1 with and without the moist physics upgrade. The dotted line represents 'no bias'.

Impact on ensemble forecasts

Testing of the ensemble system shows that the revised physics increases the activity of the model. For example, Figure 8 shows the relative increase of 250 hPa wind speed ensemble standard deviation (spread) compared to the IFS Cycle 46r1 baseline for June 2018. It is apparent that the ensemble spread is increased more strongly in regions where convection dominates perturbation growth, i.e. in the northern hemisphere (in summer) and in the tropics. Here, the spread increase persists out to day 15. This is valuable because the current operational ensemble forecasts are under-dispersive during the northern hemisphere summer for longer lead times. The increase in spread will make it possible to re-tune the stochastic model error representation.

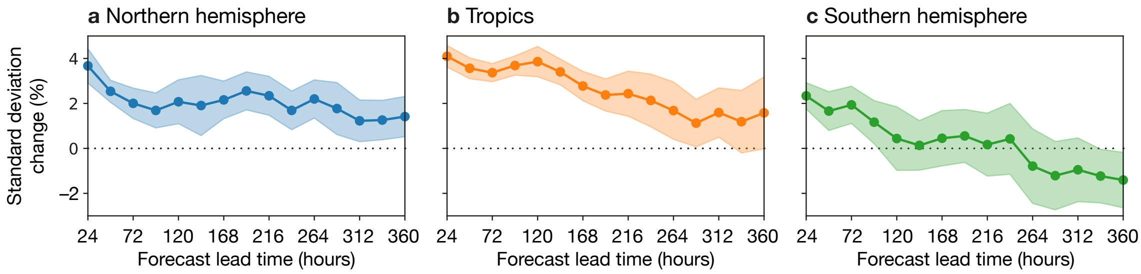

Figure 8 Relative change of 250 hPa wind speed ensemble standard deviation in a set of TCo399 ensemble forecasts using IFS Cycle 46r1 for June 2018 when the moist physics upgrade is applied, for (a) the northern hemisphere, (b) the tropics and (c) the southern hemisphere. The shaded areas show 95% confidence intervals.

Outlook

The moist physics package for IFS Cycle 48r1 is a major upgrade to the IFS which:

- addresses a number of long-standing issues in the formulation and interaction of parametrized convection, turbulent mixing and cloud-related processes
- improves the physical representation of the convective boundary layer, deep convection, cloud and precipitation in the forecast and
- reduces large-scale systematic errors in cloud and radiation.

There is also a beneficial increase in the activity of the forecast model and an improvement in the computational efficiency of the IFS by around 6%.

Final revisions and comprehensive testing of the physics upgrade across resolutions and timescales, from analysis increments to medium-range, extended-range and seasonal forecasts, will continue, in readiness for operational implementation. For the longer term, the upgrade is an important and vital step towards two strategic targets of ECMWF: ensemble forecasts at a horizontal grid spacing of about 5 km and a high-resolution ensemble where model uncertainty is represented by stochastically perturbed parametrizations (SPP; Leutbecher et al., 2017), in which parameter perturbations mainly stem from the model physics.

Concerning the future evolution of the moist physics parametrizations, we are currently testing the turbulent kinetic energy scheme developed by Météo-France. Further development of the subgrid cloud scheme and microphysics is planned in readiness for convection-permitting resolutions. Our good collaboration with the German national meteorological service (DWD) on the convection scheme continues as we have a joint implementation in the DWD's ICON model and the IFS. Furthermore, Météo-France is preparing to adapt and implement the deep convection code in its Arpège model Cy46T1.

Further reading

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