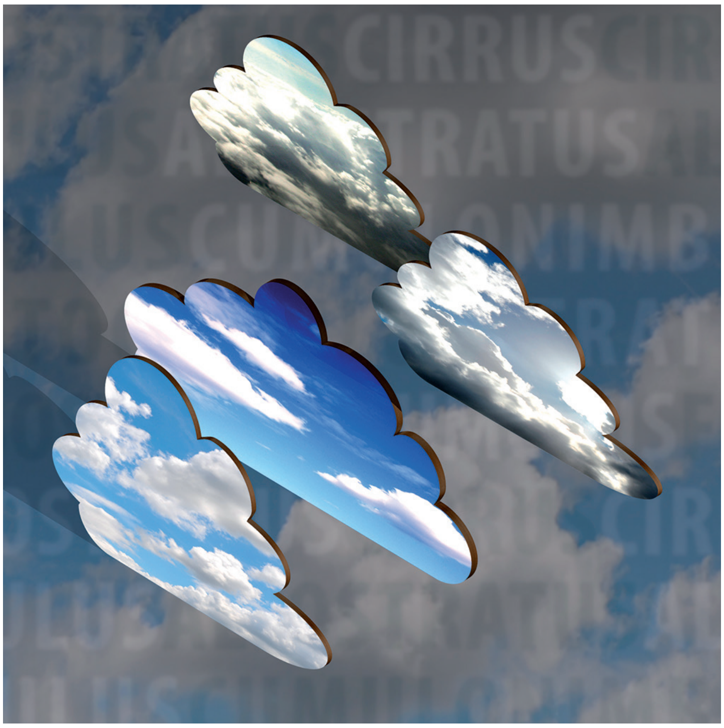
ECMWF Feature article

from Newsletter Number 129 – Autumn 2011

METEOROLOGY

An improved representation of cloud and precipitation



www.ecmwf.int/en/about/news-centre/media-resources
doi:10.21957/nfgulzhe

This article appeared in the Meteorology section of ECMWF Newsletter No. 129 – Autumn 2011, pp. 13–18.

An improved representation of cloud and precipitation

Richard Forbes, Adrian Tompkins

A major upgrade to the parametrization of stratiform cloud and precipitation was implemented in the Integrated Forecasting System (IFS) cycle 36r4, operational from 9 November 2010. This change is part of the continuing programme of development of moist physics parametrizations in the IFS, which remains a key area for improvement for Numerical Weather Prediction and an important part of the ECMWF model development strategy.

Three additional prognostic variables have been introduced to enable a more physically based representation of mixed-phase (liquid/ice) cloud and precipitating rain and snow. It is the most significant change to the structure of the cloud parametrization since tahe Tiedtke scheme was introduced operationally in 1995.

Many aspects of the model are systematically improved including the skill of precipitation forecasts, the spatial distribution of cloud ice and precipitating snow in the troposphere, the physical processes in mixed-phase cloud, and the impact of cloud and precipitation on radiation. In addition, the new scheme provides a more physically based framework for further development of the parametrization, particularly as model resolution is projected to increase in the future.

A brief history of the IFS cloud scheme is first described to put the recent changes into context, followed by the primary motivations for the upgrade and description of the new scheme. A few examples of evaluation against observations are used to highlight the improved representation of cloud and precipitation in the IFS, and the article concludes with a summary and outlook for the future.

A brief history of IFS cloud scheme developments

The Tiedtke cloud scheme, described fully in *Tiedtke* (1993), has served the IFS well over the last 15 years. The approach of parametrizing the sources and sinks of a set of prognostic cloud variables due to all the major cloud generation and dissipation processes, including convection and microphysics, made the IFS scheme unique in its time. The original Tiedtke scheme has two prognostics parameters for cloud; the first describing the fraction of the grid box covered by cloud, and the second representing the mass mixing ratio of total cloud condensate, divided into separate liquid and ice categories diagnostically according to temperature. Precipitating rain and snow are also treated diagnostically. Figure 1a shows a schematic representing the Tiedtke cloud scheme operational in the IFS from 1995 to 2010.

Since the original implementation, the scheme has been under continual development with many numerical and microphysical aspects of the scheme changed. Some of the main developments include improvements to the following.

- Ice sedimentation and autoconversion to snow.
- Subgrid precipitation coverage and evaporation.
- Numerical treatment of the cloud condensate and cloud fraction equations.
- Representation of ice supersaturation in cloud-free air.

Although the scheme has evolved significantly, the basic structure has remained essentially the same, with a prognostic cloud fraction variable and a single prognostic variable to represent cloud condensate. With increasing emphasis on cloud and precipitation in NWP and increasing resolution of the IFS model, it was clear that a number of changes were required to enable the continued improvement of the scheme both now and looking ahead for the future. Particular issues that needed to be addressed concerning precipitation advection, mixed-phase cloud, numerical issues and the physical realism of the scheme are now discussed in more detail.

AFFILIATIONS
Richard Forbes: ECMWF, Reading, UK
Adrian Tompkins: ICTP, Trieste, Italy

 doi:10.21957/nfgulzhe

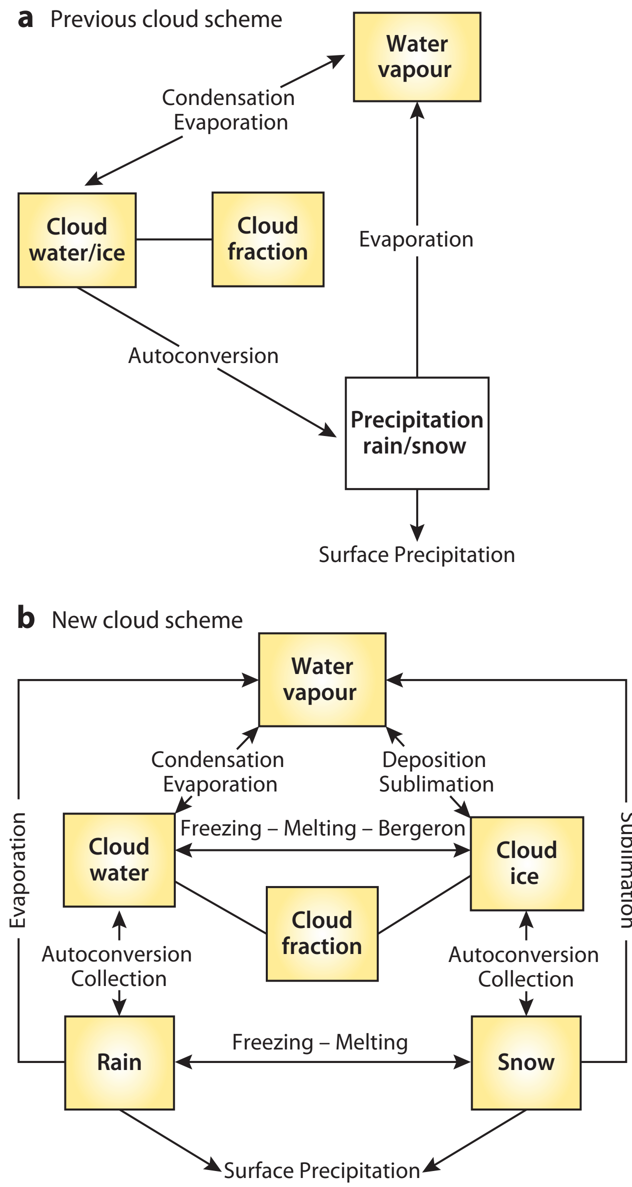


Figure 1 Schematic of the IFS cloud scheme: (a) the Tiedtke scheme with three moisture related prognostic variables operational from 1995 to 2010 (before IFS Cy36r4) and (b) the new cloud scheme with six moisture related prognostic variables (Cy36r4 onwards). Yellow boxes indicate prognostic variables.

Precipitation advection

Higher horizontal resolution and shorter timesteps mean the original diagnostic assumptions for precipitation become less valid. The diagnostic approach assumes the time taken for precipitation to fall from cloud to ground is small compared to the timestep of the model and that horizontal advection can be neglected on the spatial scale of the model grid resolution. A prognostic representation of precipitation is therefore required as the model resolution and timestep increase, particularly for snow particles which have a lower density and slower terminal fall speed than raindrops.

Mixed-phase cloud

The diagnostic approach to the mixed phase, which partitions the cloud condensate into liquid and ice according to temperature in the range 0°C to –23°C, means that both ice and supercooled liquid are always present in cloud in this temperature regime and no liquid water is allowed at colder temperatures than –23°C. The reality can be very different. For example in this sub-zero temperature range, emerging convective clouds are often all liquid, established frontal clouds often all ice and thin mid-level cloud often topped with a shallow supercooled liquid water layer with ice particles precipitating out below. Supercooled liquid water is observed down to temperatures of –30°C and colder. If the model is to begin to capture these aspects, then an additional degree of freedom is required with separate prognostic variables for liquid and ice condensate.

doi:10.21957/nfgulzhe

Numerical issues
The diagnostic mixed-phase approach also leads to a number of unrealistic numerical artefacts in the formulation of the microphysical processes, leading to a discontinuity in ice supersaturation and autoconversion of ice to snow at the mixed-phase temperature threshold (−23°C) and a lack of sedimentation of ice in the mixed phase. This significantly affects the physical representation and the spatial distribution of ice in the mixed-phase temperature range. In addition, the diagnostic approach assumes a single saturation curve in the mixed phase varying from water saturation at 0°C to ice saturation at −23°C. In reality different microphysical processes respond differently to ice saturation and water saturation, such as the deposition growth of ice crystals at the expense of water drops (the Wegener-Bergeron-Findeisen mechanism).

Physical realism
The representation of cloud with just two variables leads to a number of simplifications and approximations in the scheme. Additional degrees of freedom allows for a more physically realistic representation of cloud and precipitation microphysics that can be verified with observations.

The new cloud and precipitation scheme
The new parametrization of stratiform cloud and precipitation increases the number of prognostic variables from two (cloud fraction, cloud condensate) to five (cloud fraction, cloud liquid water, cloud ice, rain and snow). The philosophy of the original Tiedtke scheme is retained with regards to a prognostic cloud fraction and sources and sinks of all cloud variables due to the major generation and destruction processes, including detrainment from convection. However, water and ice clouds are now independent, addressing many of the issues identified above and allowing a more physically realistic representation of supercooled liquid water cloud. Rain and snow precipitation are also now able to precipitate with a determined terminal fall speed and can be advected by the three-dimensional wind.

A new multi-dimensional implicit solver is implemented for the numerical solution of the cloud and precipitation prognostic equations. Overall, the number of lines of executable code in the cloud scheme has almost doubled through the increased complexity.

Figure 1b shows a schematic of the new scheme and further information can be found in *Forbes et al.* (2011). The main changes are discussed in more detail below with examples of evaluation of different aspects of the scheme against observations.

Improved representation of precipitation
Both rain and snow precipitation are now prognostic variables, which are stored from timestep to timestep, precipitate with a terminal fall velocity and are advected by the wind. As before, the precipitation processes of generation through autoconversion from cloud, collection of cloud particles (accretion, aggregation), melting (from snow to rain) and evaporation are all included. However, there is no longer an instantaneous response of surface precipitation to the microphysical processes in the local atmospheric grid column above. With the prognostic representation, precipitation can be blown by the wind as it falls over multiple timesteps, which results in a spatially and temporally smoother precipitation field.

The advection of snow by the wind can be particularly significant in regions of orographic forcing producing persistent geographically locked precipitation. With a diagnostic precipitation scheme, precipitation often falls on the upslope and peaks of orography as an instantaneous response in the vertical to the local forcing, whereas the effect of horizontal advection by the atmospheric winds results in a downstream shift of the precipitation towards the lee of the orography and a different hydrological catchment. This effect is more significant for snow than for rain, due to the slower fall speed of snow particles and potentially longer residence time in the atmosphere.

The changes contribute to a significant improvement in global precipitation skill shown by the 1-SEEPS score in Figure 2. SEEPS (Stable Equitable Error in Probability Space) is a supplementary headline score at ECMWF used for verification of deterministic precipitation forecasts and 1-SEEPS is used so that higher values correspond to higher skill. It is an equitable score using three categories; dry, light precipitation and heavy precipitation defined by the local climatology. For more information, there is an article in the summer 2011 issue of the *ECMWF Newsletter* (*Rodwell et al.*, 2011).

doi:10.21957/nfgulzhe

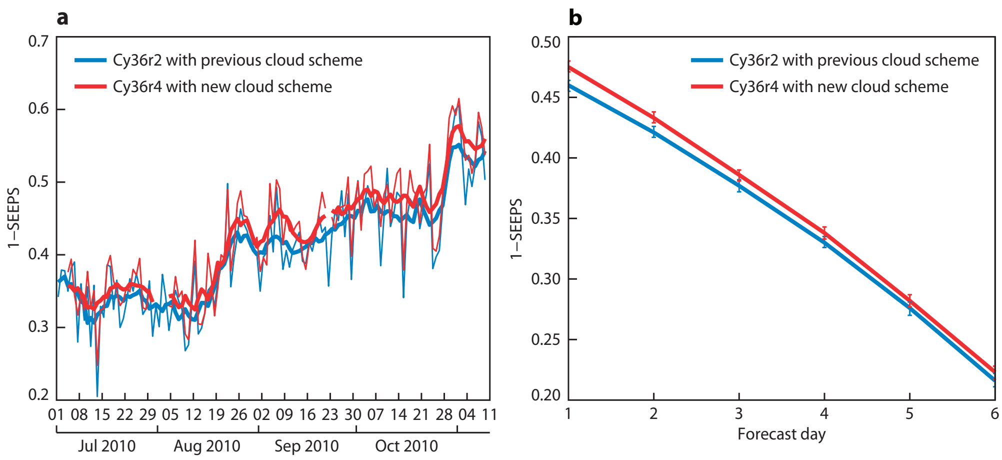


Figure 2 (a) Global precipitation skill score (1-SEEPS) for Cy36r4 with the new cloud scheme and the previous operational cycle Cy36r2 for the period 1 July to 9 November 2010 (24- to 48-hour forecast accumulations from 00 UTC forecasts). Thin lines: daily values, bold lines: running weekly average. (b) Global 1-SEEPS score averaged over the same period as a function of lead time (24-hour accumulations from 12 UTC forecasts). Higher values represent higher skill. Error bars show 95% confidence intervals.

Improved global distribution of cloud ice and snow

Modifications to the representation of ice and snow in the new scheme result in significant changes to the three-dimensional distribution of frozen particles in the model. The two-category approach is a way of representing small and large particles in the scheme. Smaller ice particles with low fall velocities associated with cloud that grows primarily by deposition are represented by the 'ice' category and 'snow' represents larger ice particles with higher fall velocities that grow through collection (aggregation). The process of 'autoconversion' is used to represent the onset of broadening of the particle size distribution through aggregation, leading to conversion of mass from the 'ice category' to the 'snow category'. The latter, representing larger particles, then precipitates at a faster rate.

Previously, the autoconversion of ice to snow only operated in the pure ice-phase temperature zone (colder than –23°C) with all cloud condensate treated by the less efficient rain autoconversion process at temperatures warmer than this threshold. Another necessary condition of the diagnostic approach to the mixed phase in the previous scheme was an assumption of zero fall velocity for ice cloud between 0°C and –23°C which then gradually increased in the pure-ice phase at colder temperatures above. These two restrictions meant the only sink of ice in the mixed-phase zone was the repartitioning into liquid and ice at every timestep and this led to artificially high ice cloud mass in the mixed-phase zone.

The new scheme has a consistent treatment of autoconversion and sedimentation for the new prognostic ice variable throughout the temperature range and therefore avoids any discontinuities at –23°C and significantly reduces the amount of ice at temperatures warmer than –23°C. Figure 3 shows the zonal cross section of the annual mean cloud ice content for the previous cloud scheme, the new scheme and an estimate derived from the CloudSat radar. All 1.7 km CloudSat footprint profiles that are estimated to be either precipitating or convective in the observation data have been removed in order to capture the 'ice cloud' part of the total cloud mass. The zonal distribution of ice in the new scheme is closer to that derived from CloudSat and no longer contains the artificial peaks seen in the diagnostic scheme in the 0°C to –23°C temperature zone.

The distribution and amount of ice cloud has important radiative impacts. Consequently the root mean square error of both net shortwave and longwave annual mean radiative fluxes at the top of the atmosphere are reduced in the new scheme compared to observations from the CERES (Clouds and the Earth's Radiant Energy System) satellite instrument. In addition the prognostic snow category is now radiatively active and one effect is to warm the troposphere.

Figure 4 shows the geographical distribution of the annual mean vertically integrated cloud ice water path from the previous cloud scheme and the combined prognostic ice and snow water path from the new scheme, as well as the estimated total ice water path derived from CloudSat. In the extra-tropics there is good agreement between the spatial distribution and magnitude of the total stratiform ice and snow water path from the new scheme and the observed estimate. The differences in the tropics over Africa, South America and the Inter-Tropical Convergence Zone (ITCZ) are where precipitation from deep convection dominates in the observations. Ice and snow in convective cores are currently not included in the model output for deriving ice water path, and this, along with the interaction of convective cores with the radiation, are potential areas for future research.

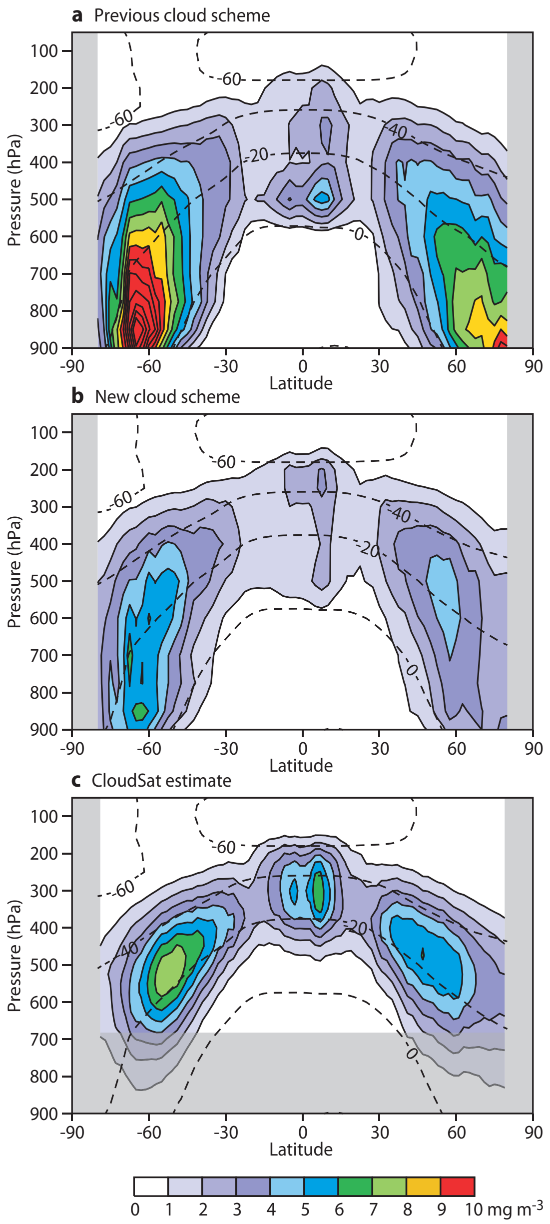


Figure 3 Zonal cross-section of annual mean cloud ice for (a) the previous IFS cloud scheme with a diagnostic mixed phase, (b) the new IFS cloud scheme with a consistent treatment of cloud ice at all temperatures and (c) the estimate derived from CloudSat (82°S to 82°N) filtering out all observed precipitating and convective profiles to obtain a closer equivalent to the model cloud ice field. Annual mean temperature is shown as dashed contours (°C). The shading indicates areas where data is absent or particularly uncertain. Note the CloudSat product has limitations; there is no reliable signal close to the surface due to contamination by surface backscatter, thin cirrus cloud is often not observed and there are assumptions about the ice/liquid partition in the mixed-phase temperature regime which will tend to lead to an underestimate of ice as temperatures approach 0°C.

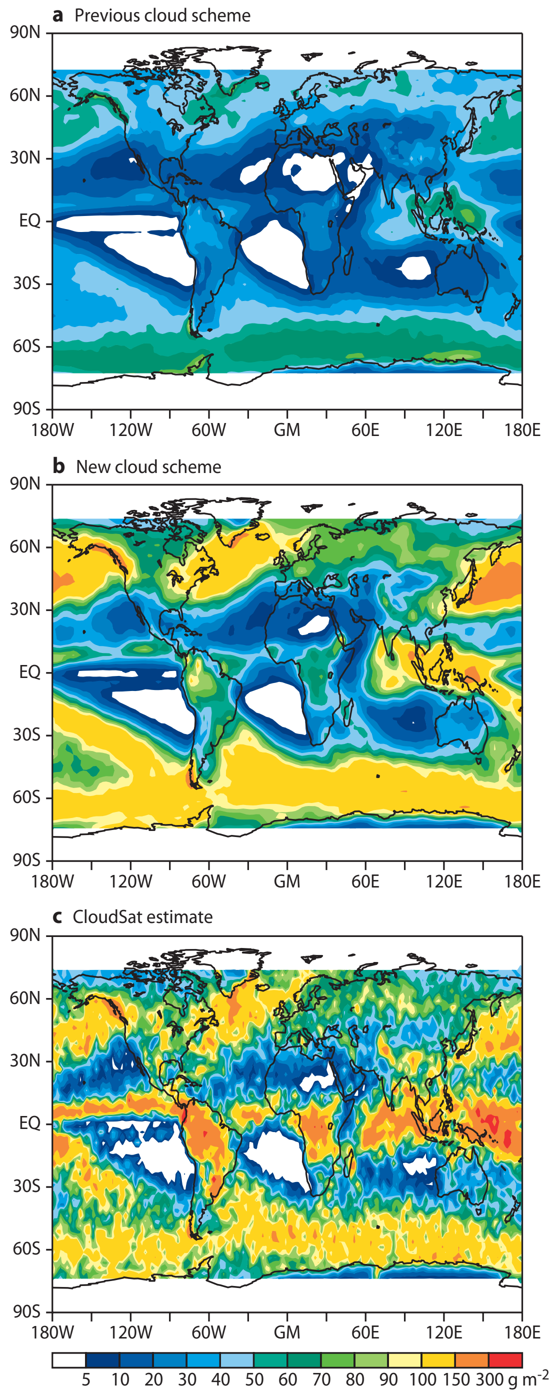


Figure 4 Annual mean vertically integrated ice water path for (a) radiatively active cloud ice from the previous cloud scheme, (b) radiatively active total cloud ice and snow from the new cloud scheme, and (c) estimate derived from CloudSat (August 2006 to July 2007), (*Waliser et al.*, 2009). The convective core precipitating snow is not included in the model output which accounts for the underestimate of ice water path in the tropics.

 doi:10.21957/nfgulzhe

Improved representation of supercooled liquid water cloud

The separate treatment of ice and water clouds now results in a wider variability of occurrence of supercooled water.

Any supersaturation with respect to water at temperatures warmer than the homogeneous freezing temperature (–38°C) is condensed as water droplets, and the new processes of ice nucleation and depositional growth of ice crystals, representing the growth of ice crystals at the expense of water droplets through the Wegener-Bergeron-Findeisen mechanism, act to transfer water mass to the ice particles. If ice is nucleated in a cloud at water saturation, the ice crystals are in an environment supersaturated with respect to ice and grow by deposition, reducing the water vapour and leading to subsaturation with respect to water. Water droplets then evaporate and the process continues with ice growth until the water droplets are completely evaporated and the water vapour is depleted to the ice saturation level. The model assumes cloud is at water saturation if liquid water is present, but reduced to ice saturation if all the water has been depleted and only ice is present.

Figure 5 shows the distribution of liquid water fractions in cloud as a function of temperature for the diagnostic temperature-dependent scheme and the wide spread of possible values for the new prognostic scheme.

After operational implementation of the scheme in November 2010, feedback from Member States' forecasters in January 2011 highlighted a problem with excessively cold temperatures in certain meteorological conditions. This quickly led to the identification of a problem in the new scheme related to the representation of supercooled liquid water. In weakly forced relatively calm overcast conditions with low cloud in the 0°C to –30°C range, there was less supercooled water in the cloud compared to the previous diagnostic scheme and sometimes it was absent. This resulted in screen-level temperatures that were systematically too cold due to excessive long-wave radiative cooling in a shallow near-surface layer through the night. Observations from aircraft and lidar remote sensing show supercooled liquid water occurs frequently at cloud top in low and midlevel clouds in the atmosphere in the form of thin layers a few hundred metres thick, often with ice precipitating out below (see Figure 6).

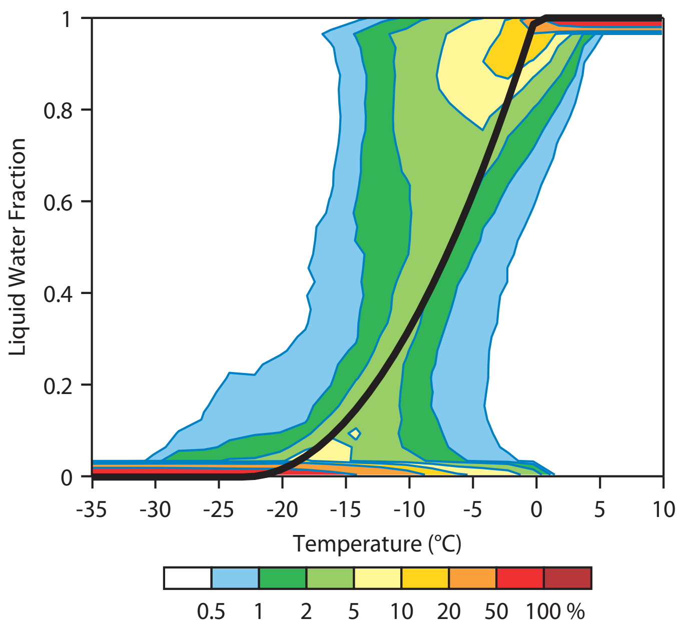


Figure 5 Global percentage occurrence (for a given temperature) of the liquid water fraction of cloud condensate for the previous diagnostic temperature-dependent mixed-phase scheme (thick black line) and the new prognostic ice/liquid scheme (shading) for a range of temperatures (on 10 January 2011). The mode of the distribution still approximately follows the temperature-dependent function, but variability is significantly increased. For example, 100% of cloud is all ice at –35°C, 100% is all liquid at +10°C, but at –10°C the cloud can vary from all ice, through varying fractions of supercooled liquid water, to all water.

The supercooled liquid water layers are the result of a fine balance between radiative cooling driving small-scale turbulent motions, production of water saturation and cloud liquid water droplets, the availability of ice nuclei, nucleation of ice crystals, deposition growth removing water vapour and fall-out of ice particles under gravity. The previous version of the model cloud scheme is not able to represent these thin supercooled layers, as by definition all cloud between 0°C and –23°C contains supercooled water. In contrast, the new scheme does represent much of the basic physics needed to represent the characteristics of these layers, but is limited partly by the coarse vertical resolution of the model and partly by remaining deficiencies in the representation of the complex microphysical processes in mixed-phase clouds.

The observations of thin supercooled liquid water layers and identified model deficiencies in weakly forced conditions inspired an improved parametrization, modifying the generation terms for supercooled liquid water and reducing the ice deposition rate near cloud top. Temperature at screen level is affected by many processes including radiation, clouds, land surface, turbulent exchange and local effects, but the two metre temperature errors associated with supercooled liquid water cloud have been significantly reduced by the changes to the cloud scheme, particularly in the winter months over north-east Europe and North America. These changes are included in the new IFS Cycle 37r3. Figure 7 shows the positive impact of these changes on the 72-hour forecast of temperature during January 2011 (i.e. warming and reduction of mean absolute error).

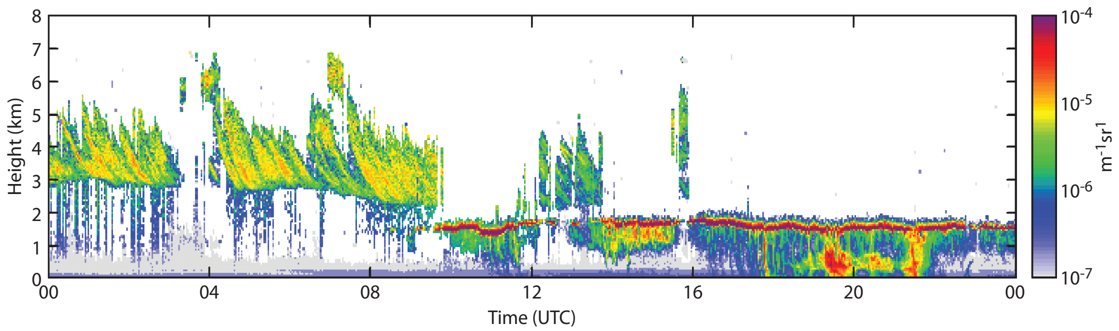


Figure 6 Timeseries of lidar backscatter coefficient from Sodankylä in northern Finland on 14 January 2011 showing the thin supercooled liquid water layers. The layer of high values of backscatter at about 1.5 km altitude after 10 UTC is typical of these latitudes and is associated with a thin liquid water layer with ice precipitating out below. (Courtesy of Finnish Meteorological Institute)

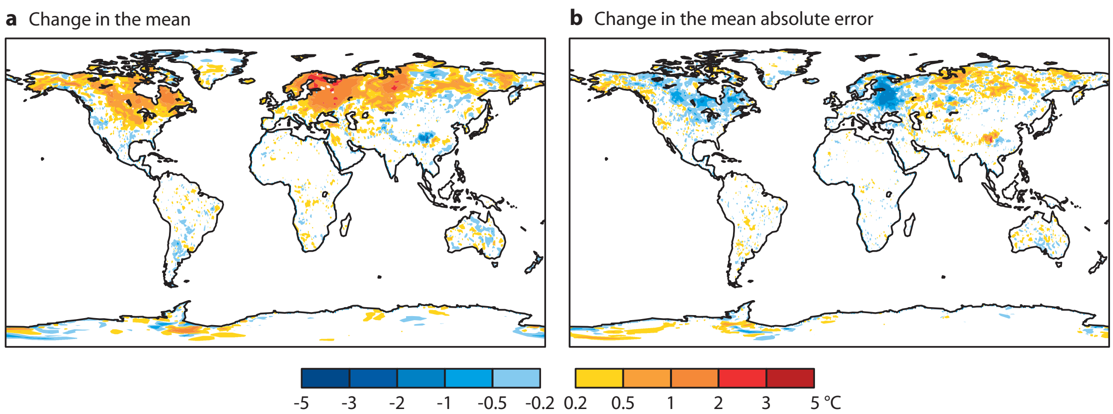


Figure 7 The impact of the mixed-phase cloud changes for IFS Cy37r3 on the 72-hour forecast of 2-metre temperature over land at 00 UTC averaged for three weeks in January 2011: (a) change in the mean and (b) change in the mean absolute error. There is a significant warming and reduction of error in regions over Europe and North America where supercooled liquid water layers most commonly occur at this time of year.

 doi:10.21957/nfgulzhe

Summary and outlook

The upgrade to the representation of cloud and precipitation in the IFS has significantly modified the cloud parametrization in terms of the number of prognostic variables, formulation of mixed-phase and precipitation processes and cloud scheme numerics. Liquid and ice cloud condensates are now determined by explicit microphysical processes rather than by a fixed function of temperature, resulting in wider variability of supercooled liquid water occurrence. Rain and snow are now advected by the wind and precipitation skill is improved.

Overall, this has been a major change to the representation of moist physics and a significant milestone towards a more physically based cloud and precipitation parametrization scheme in the IFS model. The parametrization framework is now more appropriate for a wider range of model resolutions and is closer to the typical single-moment schemes used in higher-resolution limited-area NWP and cloud resolving models (CRMs).

There are many opportunities for further development of the scheme and the focus will shift towards improving the formulation of cloud and precipitation microphysical processes to provide a stronger physical basis, improved internal consistency and a more direct link to observable parameters such as particle size distributions and particle characteristics. Ongoing evaluation against a wide range of ground based and satellite observations is a further vital activity for continued parametrization development in the IFS and improved forecasts of cloud and precipitation in NWP.

Further reading

Forbes, **R.M.**, **A.M. Tompkins** & **A. Untch**, 2011:
A new prognostic bulk-microphysics scheme for the IFS. *ECMWF Tech. Memo. No. 649*.

Rodwell, **M.J.**, **T. Haiden** & **D.S. Richardson**, 2011: Developments in precipitation verification. *ECMWF Newsletter No. 128*, 12–16.

Tiedtke, **M.**, 1993: Representation of clouds in large-scale models. *Mon. Wea. Rev.*, **121**, 3040–3061.

Waliser, **D.E. et al.**, 2009: Cloud ice: A climate model challenge with signs and expectations of progress. *J. Geophys. Res.*, **114**, D00A21, doi:10.1029/2008JD010015.