Representing cloud and precipitation in the ECMWF global model

Richard Forbes and Maike Ahlgrimm

European Centre for Medium-Range Weather Forecasts
Reading, UK

1. Introduction

The ECMWF Integrated Forecasting System (IFS) provides global forecasts from medium-range to seasonal timescales using a range of model resolutions, from ~100 km to 16 km grid resolutions, with plans for higher resolution in the future. There is therefore a need for physical parametrizations to be applicable across a wide range of spatial and temporal scales. The strategy for development of physical parameterisations at ECMWF over the coming years places particular emphasis on moist physics and there are still many questions of how best to represent cloud and precipitation processes, their subgrid-scale heterogeneity and impacts on the forecasts from the global to the convective scale.

For the parametrization of cloud and precipitation, we can conceptually split the problem into "microphysics" and "macrophysics", where the former describes the representation of micro-scale physical processes and the collections of particles within some small volume, and the latter describes the subgrid-scale variability of hydrometeor contents and humidity and to some extent the geometry of the cloud, precipitation and vertical overlap within the grid column. In order to make progress, we need to address both the microphysical and macrophysical aspects and use observations to constrain the parametrizations wherever possible. There is always a balance between complexity of the parametrization (to give enough degrees of freedom to represent the real atmosphere), the limits of our understanding (from observations, theory and process models) and computational expense (due to limited resources). However, what is particularly important in order to improve any modelling system is an understanding of the impacts of each part of the parametrization on different aspects of the model evolution.

A brief overview of the current parametrization of cloud and precipitation in the ECMWF IFS global model is given in section 2 with regard to microphysics and the subgrid cloud scheme (macrophysics). Section 3 discusses impacts of cloud and precipitation processes, with an example of the effect of thin super-cooled liquid topped boundary layer cloud on radiation and 2m temperature forecasts. Section 4 concludes with a summary of some of the general issues to consider for the future development of cloud and precipitation parametrization.

2. Parametrization of cloud and precipitation in the ECMWF IFS model

The "Tiedtke" cloud scheme, described in Tiedtke (1993), has served the IFS well over the last 15 years with 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. The original Tiedtke scheme has two prognostic 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 1(a) shows a schematic representing the Tiedtke cloud scheme operational in the IFS from 1995 to November 2010.

Since the original implementation, the scheme has been under continual development with many changes to the numerical and microphysical aspects of the scheme. Some of the main developments include improvements to ice sedimentation and autoconversion to snow, subgrid precipitation coverage/precipitation evaporation (Jakob and Klein 1999, 2000), the numerics of the cloud scheme and the representation of ice supersaturation in cloud-free air (Tompkins et al., 2007).

A major upgrade to the parametrization of stratiform cloud and precipitation was implemented in IFS Cycle 36r4, operational from 9 November 2010, and increased 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 was retained with regards to a prognostic cloud fraction and sources and sinks of all cloud variables including detrainment from convection. However, water and ice clouds became independent variables, allowing a more physically realistic representation of super-cooled liquid water cloud. Rain and snow were also able to precipitate with a determined terminal fall speed and be advected by the three-dimensional wind, and a new multi-

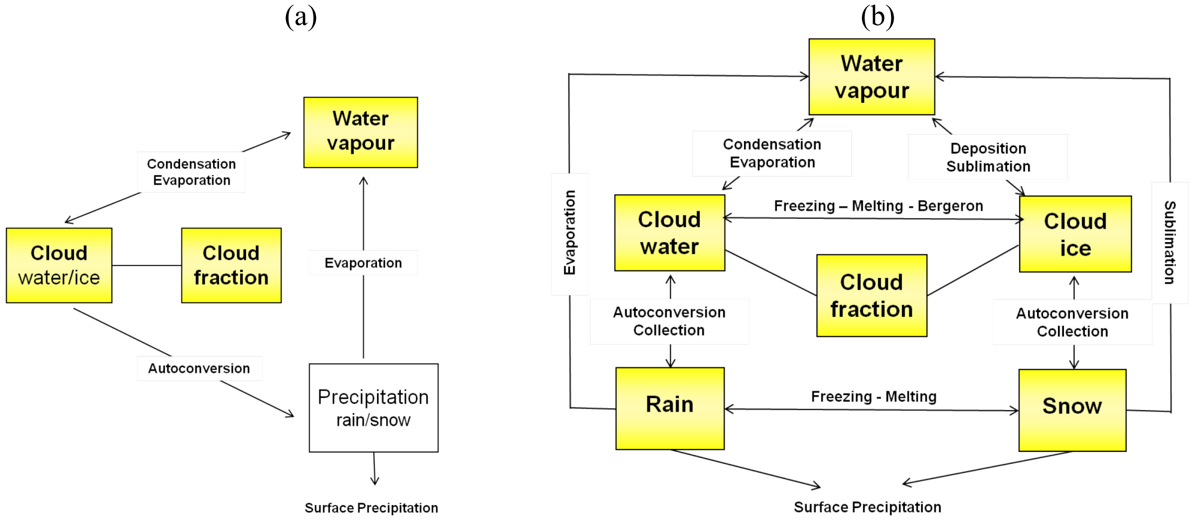

Figure 1: Schematic of the IFS cloud scheme: (a) the Tiedtke scheme with three moisture related prognostic variables operational from 1995 to 2010 (before IFS Cy36r4) and (b) the new cloud scheme with six moisture related prognostic variables (Cy36r4 onwards). Shaded boxes indicate prognostic variables.

dimensional implicit solver was implemented for the numerical solution of the cloud and precipitation prognostic equations. Figure 1(b) shows a schematic of the new scheme and further information can be found in Forbes et al. (2011).

For the "macrophysics", the IFS represents subgrid-scale cloud with a cloud fraction prognostic variable. A mixed 'uniform-delta' total water PDF is assumed for some of the processes (including condensation). This is shown in Figure 2(a) with an assumption of uniform humidity variability in the clear sky part of the grid box (a "top-hat" function) and homogeneous condensate (a delta function) in the cloudy part. A critical relative humidity is required to determine the width of the humidity distribution when there is no cloud. Note that some but not all of the sources and sinks of condensate and cloud fraction are consistent with this PDF assumption.

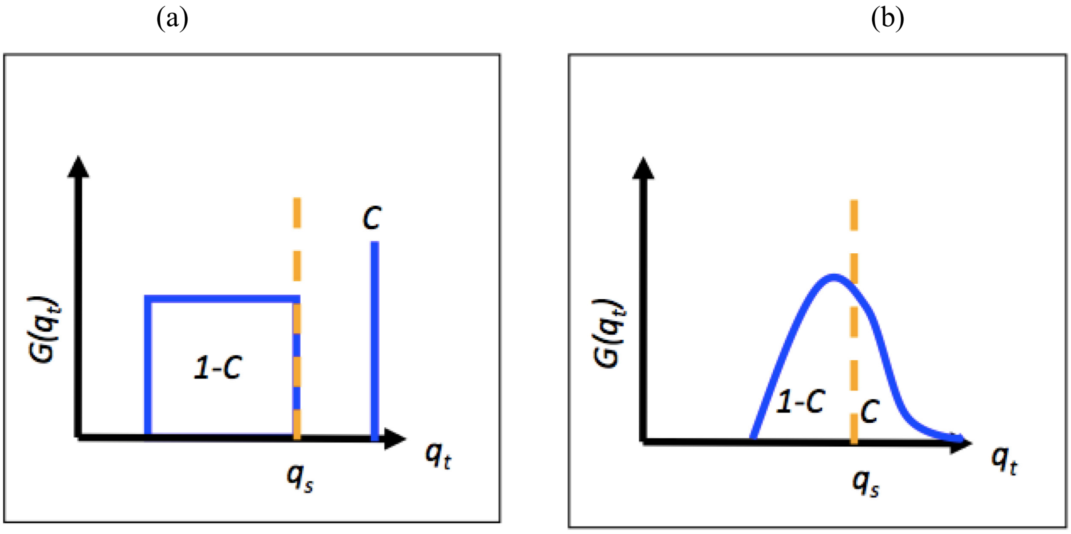

Figure 2: Schematic of the sub-grid PDF, G(q_t), of total water, q_t, for: (a) the Tiedtke (1993) scheme and (b) the Tompkins (2002) scheme. qs is the saturation specific humidity, C is the cloud fraction (0-1) which is the integral of the total water distribution to the right of saturation, and (1-C) is the clear sky fraction.

There are a number of different approaches for representing subgrid-scale cloud heterogeneity in other operational and research models, but almost all have some assumption about an underlying PDF of humidity and cloud or total water (commonly termed "statistical cloud schemes"). A variety of more or less complex symmetrical and skewed functional forms based on observations have been used, such as uniform, triangular, log-normal, Beta and double Gaussian (Sundquist et al. 1989, Smith 1990, Bony and Emanuel 2001, Lewellen and Yoh 1993, Golaz et al. 2002, Tompkins 2002). Schemes have different numbers of diagnostic or prognostic variables and therefore very different degrees of freedom. For example, the Smith (1990) scheme provides a purely diagnostic cloud fraction based on relative humidity, whereas the Tompkins (2002) scheme considers the PDF of subgrid variability of total water using a positively skewed Beta function with prognostic variables for effectively three moments (mean, variance and skewness) and sources and sinks due to physical processes such as convection, turbulence and precipitation.

In comparing the prognostic cloud fraction approach (Tiedtke, 1993) with the prognostic PDF moments approach (e.g. Tompkins 2002), note that a warm-phase version of the Tiedtke scheme (gridbox mean humidity, condensate, cloud fraction) in principle has the same number of prognostic variables to describe a total-water PDF as the Tompkins scheme with mean, variance and skewness and a specified functional form for the PDF. However, each of the schemes has advantages and disadvantages. With a defined form of PDF and prognostic variables for mean, variance and skewness, the subgrid heterogeneity of humidity and cloud is always known and the derived condensate and cloud fraction are always self-consistent with the underlying PDF. However, parametrizing the sources and sinks of the PDF moments is difficult and the total water approach only directly applies to the warm phase cloud where condensation is local, fast and reversible. For ice cloud and mixed-phase cloud, where processes may not be in equilibrium and super-saturation may exist, and for precipitation which is non-local due to sedimentation, the total water PDF assumptions no longer hold and additional prognostic variables would be required.

A further question is whether the chosen functional form of the PDF is able to represent the full range of variability as observed in the atmosphere. In contrast, the Tiedtke-type approach has physical quantities (integral properties of the PDF) as prognostic variables for which sources and sinks are conceptually easier to define, additional variables for the ice phase and precipitation are straight forward within the same framework and there is no restriction of a continuous functional form to the PDF to limit the possible combinations of cloud fraction and condensate amount. However, there are a number of disadvantages of the Tiedtke scheme. Self-consistency of condensate and cloud fraction is not always guaranteed, there is a loss of information whenever the grid-box is completely clear or 100% cloudy and there is a lack of a consistent approach to heterogeneity of humidity, cloud and precipitation.

3. Understanding impacts of cloud and precipitation

When thinking about the appropriate formulation and complexity of microphysics in a GCM, we need to understand the cloud and precipitation parametrization in terms of impacts on the hydrological cycle, radiation and dynamics (through diabatic heating), and what we are able to constrain with observations. If we refer to the parametrization schematic in Figure 1b, the emphasis for hydrological impacts is on the representation of precipitation (snow and rain). For radiative impacts, the cloud variables (liquid, ice) are most important as the smaller particles dominate over larger precipitation size particles. For dynamical impacts it is the diabatic heating and cooling from phase changes that is of primary importance. These are first order considerations that help to understand how a small change to microphysical assumptions in the cloud parametrization can have large-scale impacts. However, it is also a rather simplistic viewpoint, as of course there are many interdependencies and non-linear interactions, and overall we are aiming to represent the correct impacts of all aspects of the cloud and precipitation.

One example is a change to the sedimentation fall speed of ice particles that may be due to an improved assumption of particle size distribution. Reducing ice particle fall speeds increases the amount of ice cloud in the upper troposphere and leads to increased radiative warming at these altitudes. The corresponding increase in stability in the mid- to upper troposphere results in a small reduction in the activity of convection in the tropics. So the microphysical change has a large-scale

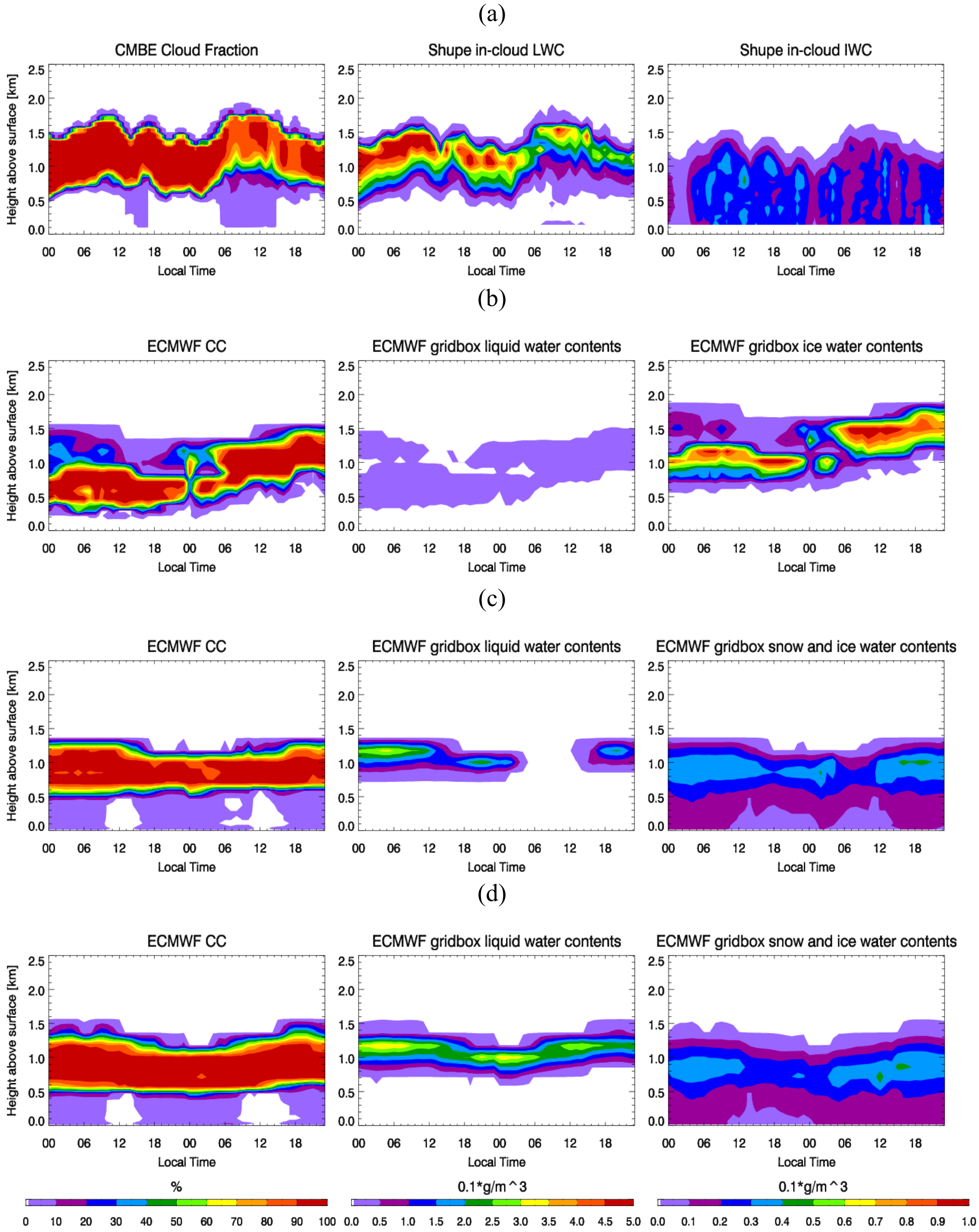

Figure 3: Cloud fraction (left), cloud liquid water contents (center) and cloud ice water contents (right) for a single layer mixed-phase cloud observed during October 8/9 2004 at the ARM North Slopes of Alaska (NSA) site during the MPACE observational campaign. (a) observations derived from remote sensing, (b) the ECMWF model with old diagnostic mixed-phase cloud scheme, (c) the new cloud scheme with separate liquid and ice prognostic variables and (d) the new cloud scheme including a parameterization to enhance supercooled liquid layers at cloud top.

impact on the tropical circulation that can be understood in simple terms. A different example highlighting the role of latent heat transfer is the impact of evaporative cooling of snow on the development of frontal cyclones. Parker and Thorpe (1995) describe the impact on the downdraught beneath the frontal surface from snow evaporation in an idealised model and Forbes and Clark (2003) extend the study to a real case using an NWP model. The strength of the downdraught, which can be associated with strong damaging surface winds in intense cyclones (Browning, 2004) is dependent on the depth of the layer of evaporative cooling which is sensitive to the assumptions of particle size distribution, evaporation rate and fall speed in the microphysical parametrization (Forbes and Clark, 2003)

A third example is described here in more detail; the representation of supercooled liquid water in the IFS with large-scale impacts on the radiation and consequently 2m temperature over land. The major upgrade to the IFS cloud parametrization for cycle 36r4 included a change from a mixed-phase liquid/ice cloud split based on a diagnostic function of temperature (from all liquid at 0°C to all ice at -23°C) to separate prognostic variables for cloud liquid water and cloud ice. 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. This results in a wide range of super-cooled liquid water occurrence for a given temperature and is physically more realistic.

However, since operational implementation of the scheme in November 2010, it became apparent that there were certain meteorological situations, weakly forced relatively calm overcast conditions with low cloud in the 0°C to -30°C range, where super-cooled water was low

or even absent in the cloud and screen level temperatures were systematically too cold due to excessive long-wave radiative cooling at night. Observations from aircraft and lidar remote sensing show super-cooled 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 falling out below. The super-cooled 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 super-cooled layers, as by definition all cloud between 0°C and -23°C contains super-cooled 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 super-cooled liquid water layers and model deficiencies in weakly forced conditions inspired an improved parametrization, modifying the generation terms for super-cooled liquid water and reducing the ice deposition rate near cloud top. Figure 3 shows a timeseries of an Arctic mixed-phase boundary layer cloud observed during the Mixed-Phase Arctic Cloud Experiment (M-PACE) observational campaign (Verlinde et al. 2007, Klein et al. 2009) with supercooled liquid topped boundary layer cloud and ice falling out below (Fig. 3a). The figure also shows the equivalent timeseries from IFS simulations of the case study with different versions of the microphysics. The version with diagnostic mixed phase (Fig. 3b) has small amounts of supercooled liquid water everywhere in the cloud (by definition, as the cloud temperature is around -10°C) and a different vertical structure of cloud fraction and condensate amount.

In contrast, the new scheme with separate prognostic variables for the liquid and ice is able to reproduce the structure of the cloud with supercooled liquid at the top and ice below (Fig 3c). However, the supercooled liquid water is depleted for part of the second day. The third model version with a parametrization for the decreased deposition rate at cloud top, to account for the limitations of vertical resolution, is able to keep the supercooled water throughout the period (Fig 3d).

The impact on the radiation for this case study can be seen in Figure 4, with the diagnostic scheme (OLD) overestimating the surface shortwave irradiance and underestimating the downwelling longwave radiation. The new prognostic scheme (NEW) improves the radiation on the first day, but is worse on the second day due to the missing supercooled water. The modified scheme (LAYERS) gives the surface radiation closest to that observed.

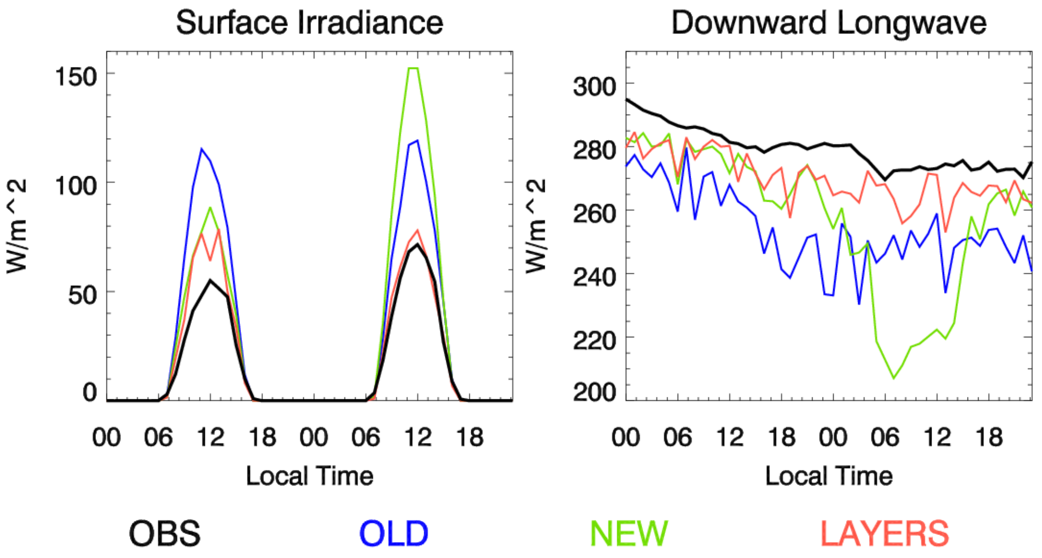

Figure 4: Impact of model changes on surface radiation for single layer mixed-phase Arctic cloud example. Observations are shown in black, the ECMWF model with old cloud scheme in blue, ECMWF model results with the new cloud scheme in green and results from the new cloud scheme with supercooled layer parameterization in red.

These impacts of supercooled water in boundary layer clouds on the radiation, particularly the downwelling longwave in winter high latitudes, can have a significant impact on temperature near the surface. The improvements in the IFS were not just seen in the case study described above, but also over large areas in the winter months in north-east Europe and North America where these type of clouds are common. Figure 5 shows the positive impact of these changes on the 00 UTC 72 hour forecast 2m temperature during January 2011 (warming, Fig 5a, and reduction of mean absolute error, Fig 5b). There is also a significant larger scale impact on the shortwave radiation in the Southern Hemisphere storm track with increased reflection, reducing a long-standing bias common to many GCMs (not shown).

This example illustrates the impact of a change to the microphysical processes (in this case the ice deposition rate in mixed-phase cloud) on the radiation, which directly impacts the 2 metre temperature (of particular interest to forecast users) and the top of atmosphere radiation (of interest to NWP and climate) on large-scales.

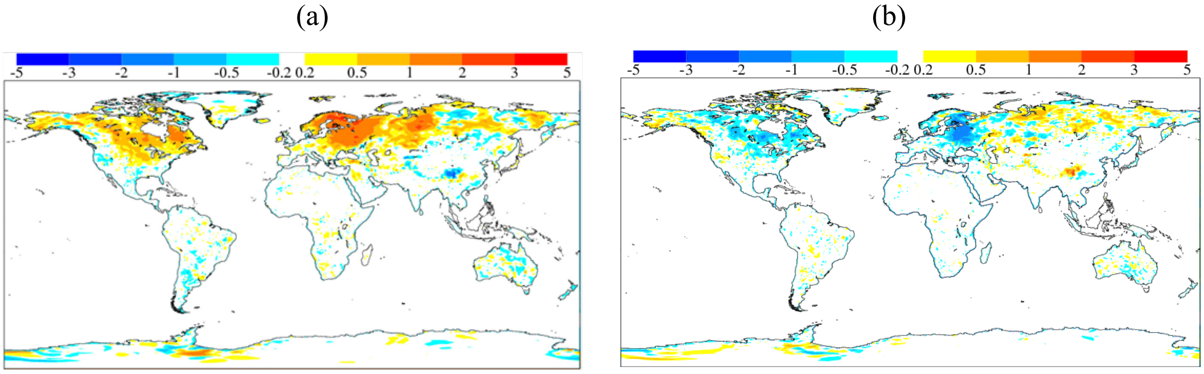

Figure 5: Impact on 2 metre temperature (°C) over land (72hr forecast for January 2011) for supercooled liquid water changes (a) mean temperature change, (b) change in mean absolute error when compared to SYNOP stations. There is a significant warming and reduction of error in regions over Europe and North America where super-cooled liquid water layers most commonly occur at this time of year.

4. Summary and considerations for the future

The parametrization of cloud and precipitation is an important component of Numerical Weather Prediction and climate models and here we have discussed some of the issues to consider in the parametrization development process including,

- a need for parametrizations that are physically based and have the appropriate degrees of freedom to represent the important aspects of the real world.
- a need to understand our cloud and precipitation parametrization in terms of impacts on the hydrological cycle, radiation and dynamics through latent heating/cooling.
- a need for appropriate complexity for the model and application – a more complex parametrization provides more degrees of freedom, but does not always lead to a better parametrization in terms of impacts.

There are still many uncertainties and questions that remain for cloud parametrization development:

- Can we constrain the parametrization sufficiently with observations?
- Are we taking sufficient advantage of current observations and their synergies to inform physically based parametrization development. What gaps remain?
- How should we formulate parametrizations of sub-grid variability (humidity, cloud, precipitation, temperature, vertical velocity) for the warm phase, ice phase and mixed phase?
- Can we make our cloud microphysics and subgrid-scale variability assumptions consistent across all model parametrizations (microphysics, convection, radiation)?

- How do we determine the right balance between complexity, accuracy and computational efficiency?
- How can we build parametrizations that work across a wide range of spatial scales (model resolutions)?

The workshop addresses many of these questions and further details of the discussions and recommendations can be found in the working group summaries available online at www.ecmwf.int.

5. References

Bony, S. and K. A. Emanuel, 2001: A parameterization of the cloudiness associated with cumulus convection: Evaluation using TOGA COARE data, *J. Atmos. Sci.*, **58**, 3158–3183.

Browning, K. A., 2004: The sting at the end of the tail: Damaging winds associated with extratropical cyclones. *Q. J. R. Meteorol. Soc.*, **130**, 375–399.

Forbes, R. M., and Clark, P. A., 2003: Sensitivity of extra-tropical cyclone mesoscale structure to the parametrization of ice microphysical processes. *Q. J. R. Meteorol. Soc.*, **129**, 1123-1148.

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

Golaz, J., V. E. Larson, and W. R. Cotton, 2002: A PDF-based parameterization for boundary layer clouds. Part I: Method and model description, *J. Atmos. Sci.*, **59**, 3540–3551.

Jakob, C., and S. A. Klein, 1999: The role of vertically varying cloud fraction in the parameterization of microphysical processes in the ECMWF model. *Quart. J. Roy. Meteor. Soc.*, **125**, 941–965.

Jakob, C. and S. A. Klein, 2000: A parametrization of the effects of cloud and precipitation overlap for use in general-circulation models. *Quart. J. Roy. Meteorol. Soc.*, **126**: 2525–2544.

Klein S. A., et al., 2009: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. I: single-layer cloud. *Q. J. R. Meteorol. Soc.,* **135**, 979–1002.

Lewellen, W. S. and S. Yoh, 1993: Binormal model of ensemble partial cloudiness, *J. Atmos. Sci.*, **50**, 1228–1237.

Parker, D. J. and A. J. Thorpe, 1995: The role of snow sublimation in frontogenesis. *Q. J. Roy. Meteorol. Soc.,* **121**, 763-782.

Smith, R. N. B., 1990: A scheme for predicting layer clouds and their water-content in a general-circulation model, *Q. J. R. Meteorol. Soc.*, **116**, 435–460.

Sundqvist H., Berge E., Kristjansson J. E., 1989: Condensation and cloud parameterization studies with a mesoscale numerical weather predicition model. *Mon. Wea. Rev.* **117**, 1641–1657.

Tiedtke, M. 1993: Representation of clouds in large scale models. *Mon. Wea. Rev.*, **117**, 1779-1800.

Tompkins, A. M., 2002: A Prognostic Parameterization for the Subgrid-Scale Variability of Water Vapor and Clouds in Large-Scale Models and Its Use to Diagnose Cloud Cover. *J. Atmos. Sci.*, **59**, 1917–1942.

Tompkins, A. M., K. Gierens, G. Rädel, 2007: Ice supersaturation in the ECMWF integrated forecast system. *Q. J. R. Meteorol. Soc.,* **133**, 53–63.

Verlinde, J., et al., 2007: The Mixed-Phase Arctic Cloud Experiment, *Bull. Amer. Meteor. Soc.*, **88**, 205-221.