Modelling snow over Antarctica in the ECMWF land surface model: Current issues and perspectives

G. Balsamo, E. Dutra, A. Beljaars

Antarctica snow is a special case that the new snow parameterization (Dutra et al. 2010) is not currently addressing.

Snow albedo (=0.8) and snow density (=300 kg/m3) and the thickness of the thermally active snow layer (=1m) are all fixed quantities.

A retuning of the snow albedo was previously shown to be very effective for addressing the mean bias during Antarctic summer

verified with observations taken at Dome-Concordia station (and reducing the model warm bias).

However the amplitude of the diurnal cycle in near-surface temperatures is still largely underestimated.

Sensitivity experiments to the thickness of the snow layer which is thermally active in the energy budget are shown and

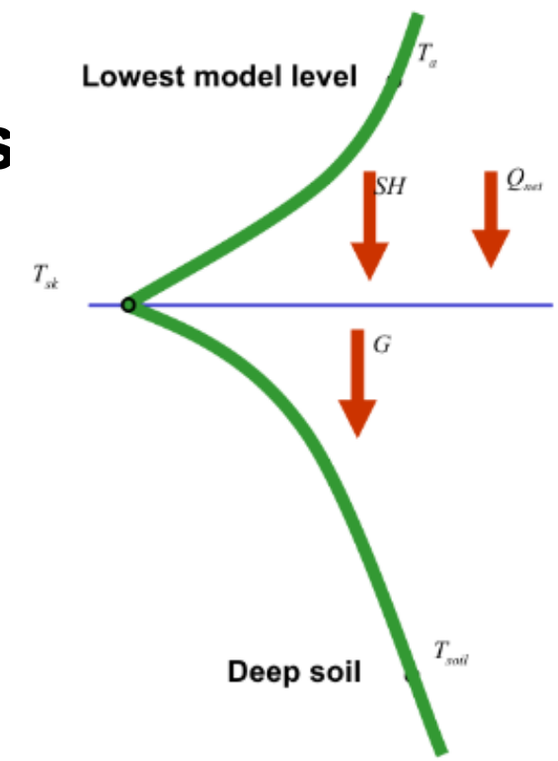
the perspectives of a multi-layer snow scheme (Dutra et al. 2011), as already tested in EC-EARTH are discussed.

Concordiasi Workshop, NCAR Boulder, 21-22 Oct 2011

ECMWF

Outlook

- **The new snow scheme**
  - **The key role of snow density**
  - **Antarctica/Greenland special cases**
- **Impact of albedo changes on mean bias**
  - **Sensitivity in long integrations**
  - **Sensitivity in short-term forecasts**
  - **Impact on scores**
- **Impact of thermally-active snow-layer changes**
- **Conclusions & Perspectives**



Land surface model status (as in CY36R4, and S4)

ECMWF newsletter article in the 2011 Spring issue

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METEOROLOGY

Evolution of land-surface processes in the IFS

GIANPAOLO BALSAMO, SOUHAIL BOUSSETTA, EMANUEL DUTRA, ANTON BELJAARS, PEDRO VITERBO, BART VAN DEN HURK

MAJOR UPGRADES have been implemented over the last few years in the soil hydrology, snow and vegetation components of the ECMWF land-surface parametrization. Compared to the scheme used in ERA-Interim and ERA-40 reanalyses, the current model has an improved match to soil moisture and snow field-site observations with a beneficial impact on the forecasts of surface energy and water fluxes and near-surface temperature and humidity. This is verified by conventional synoptic observations and by dedicated flux-tower sites for forecasts ranging from daily to seasonal. The gain in hydrological consistency is also of crucial importance for data assimilation of land-surface satellite observations in water sensitive channels. The scheme described here, currently used for daily medium-range forecasts, will be adopted by the new Seasonal Forecasting System and included in future reanalyses.

A brief description of the main hydrological components of the land-surface model with selected validation results will now be presented followed by an outlook for future research activities.

Development of the land-surface model

In recent years the land-surface modelling at ECMWF has been extensively revised. An improved soil hydrology (*Balsamo et al.*, 2009), a new snow scheme (*Dutra et al.*, 2010) and a multi-year satellite-based vegetation climatology (*Boussetta et al.*, 2011) have been included in the operational Integrated Forecasting System (IFS). These have had a positive impact on both the global hydrological water cycle and near-surface temperatures compared to the TESSEL (Tiled ECMWF Scheme for Surface Exchanges over Land) scheme which was used in the ECMWF's ERA-40 and ERA-Interim reanalyses.

In particular the soil hydrology affected the quality of seasonal predictions during extreme events associated with soil moisture-precipitation feedback as in the European summer heat-wave in 2003 (*Weisheimer et al.*, 2011). The new snow scheme improved the thermal energy exchange at the surface with a substantial reduction of near-surface temperature errors in snow-dominated areas (i.e. northern territories of Eurasia and Canada).

More recently, the introduction of a monthly climatology for vegetation Leaf Area Index (LAI) to replace the fixed maximum LAI has shown a reduction of near-surface temperature errors in the tropical and mid-latitude areas, particularly evident in spring and summer. At the same time the bare ground evaporation has been enhanced over deserts by adopting a lower stress threshold than for vegetation. This is in agreement with experimental findings (e.g. *Mahfouf & Noilhan*, 1991) and results in a more realistic soil moisture for drylands.

The participation in international projects such as GLACE2 (Global Land-Atmosphere Coupling Experiment-2) and AMMA (African Monsoon Multidisciplinary Analysis), in which the ECMWF model was coupled with a realistic set of soil moisture fields, have improved the understanding of the mechanisms and areas of strong coupling between the land surface and the atmosphere.

The land-surface components

TESSEL as documented by van den *Hurk et al.* (2000) and *Viterbo & Beljaars* (1995) is the backbone of the current operational land-surface scheme at ECMWF. It includes up to six land-surface tiles (bare ground, low and high vegetation, intercepted water, and shaded and exposed snow) which can co-exist under the same atmospheric grid-box. Recent revisions of the soil and snow hydrology as well as vegetation characteristics are illustrated in Figure 1.

Soil hydrology

A revised soil hydrology in TESSEL was investigated by van den *Hurk & Viterbo* (2003) for the Baltic basin. These model developments were a response to known weaknesses of the TESSEL hydrology: specifically the choice of a single global soil texture, which does not characterize different soil moisture regimes, and an infiltration-excess runoff scheme which produces hardly any surface runoff. Therefore, a revised formulation of the soil hydrological conductivity and diffusivity (spatially variable according to a global soil texture map) and surface runoff (based on the variable infiltration capacity approach) were introduced in IFS Cy32r3 in November 2007. *Balsamo et al.* (2009) verified the impact of HTESSEL from field site to global atmospheric coupled experiments and in data assimilation.

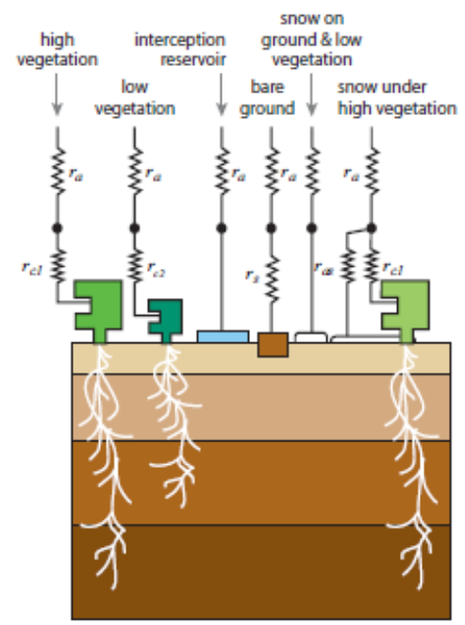
Snow hydrology

A fully revised snow scheme has been introduced in 2009 to improve the existing scheme based on *Douville et al.* (1995). The snow density formulation was changed and a liquid water storage in the snow-pack was introduced, which also allows the interception of rainfall. On the radiative side, the snow albedo and the snow cover fraction have been revised and the forest albedo in presence of snow has been retuned based on MODIS satellite estimates. A detailed description of the new snow scheme and a verification from field site experiments to global offline simulations is presented in *Dutra et al.* (2010). The results showed an improved evolution of the simulated snow-pack with positive effects on the timing of runoff and terrestrial water storage variation and a better match of the albedo to satellite products.

TESSEL (June 2000)

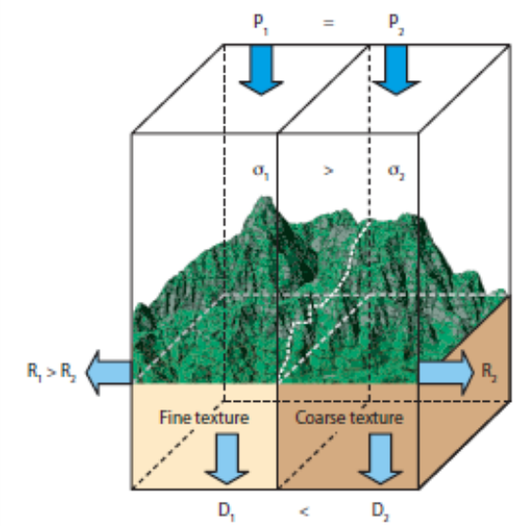
Van den Hurk et al. (2000)
Viterbo & Beljaars (1995), *Viterbo et al.* (1999)
- Up to 8 tiles (binary Land-Sea mask)
- GLCC vegetation (BATS-like)
- ERA-40 and ERA-Interim scheme

Land surface tiles in ERA-40/ERA-Interim surface scheme



Hydrology TESSEL (November 2007)

Balsamo et al. (2009)
van den Hurk & Viterbo (2003)
- Global Soil Texture (FAO)
- New hydraulic properties
- Variable infiltration capacity and surface run-off revision



New snow (March and September 2009)

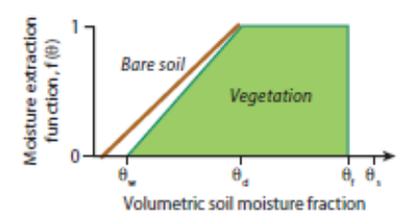
Dutra et al. (2010)
- Revised snow density
- Liquid water reservoir
- Revision of albedo and sub-grid snow cover

New Leaf Area Index (November 2010)

Boussetta et al. (2011)
- New satellite-based Leaf Area Index

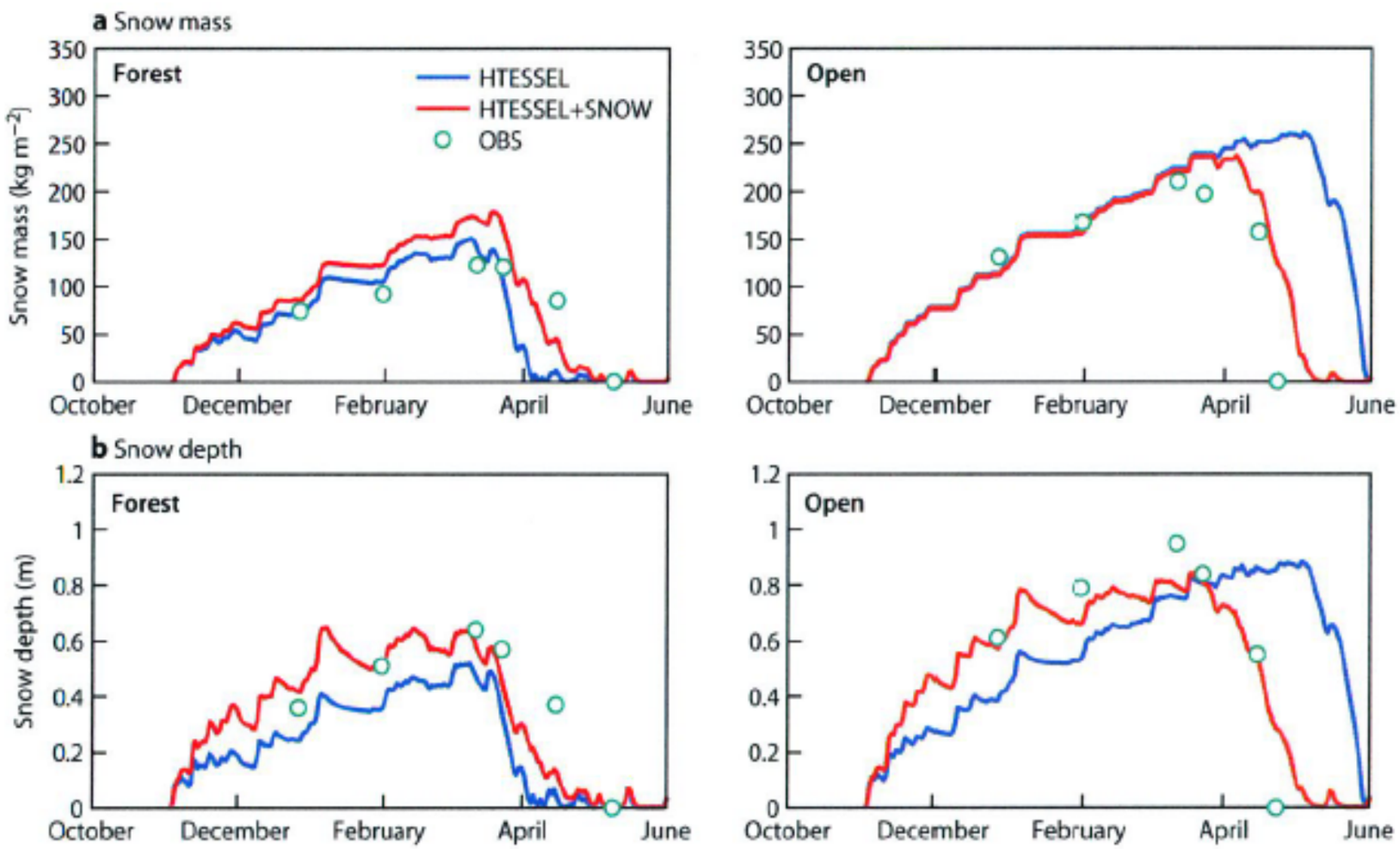
Soil Evaporation (November 2010)

Based on *Mahfouf & Noilhan* (1991)



New snow scheme

(Dutra et al. 2010, JHM)



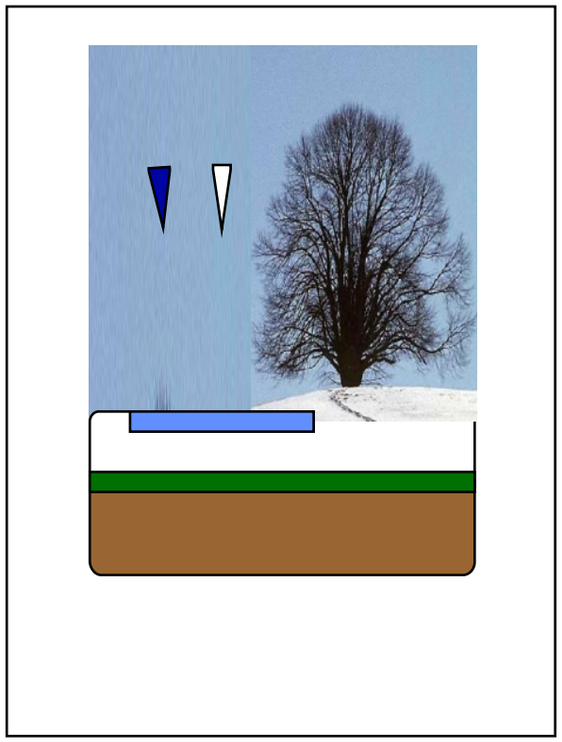
- **NEW SNOW**

  Dutra et al. (2010)

  Revised snow density

  Liquid water reservoir

  Revision of Albedo
  and sub-grid snow cover



The improvement is obtained with no increase in complexity of the snow scheme which still considers a single slab and only 4 prognostic snow variables:
albedo, mass, density, and temperature

Liquid Water in the snow-pack and new snow density formulation

- **A diagnostic formulation can take into account liquid water in the snow pack without new prognostic variable (similar to soil ice)**

$$\left(\rho C\right)_{sn} D_{sn} \frac{\partial T_{sn}}{\partial t} = R_{sn}^{N} + L_s E_{sn} + H_{sn} - G_{sn}^{B} - Q_{sn} - Q_{sn}^{INT}$$

$$Q_{sn}^{INT} = L_f M_{sn}^{INT} = L_f \frac{\partial S_l}{\partial t}$$

$$S_l = S_l\left(T_{sn}, S\right) \approx f\left(T_{sn}\right) S_l^c\left(S, \rho_{sn}\right)$$

$$f\left(T_{sn}\right) = \begin{cases} 0 & , T_{sn} < T_f - d/2 \\ 1 + \sin\left(\frac{\pi\left(T_{sn} - T_f\right)}{d}\right) & , T_{sn} \geq T_f - d/2 \end{cases}$$

- **The liquid reservoir is function of temperature, snow mass and snow density**

$$S_l^c = S\left[r_{l,\min} + \left(r_{l,\max} - r_{l,\min}\right)\max\left(0, \left(\rho_{l,r} - \rho_{sn}\right)/\rho_{l,r}\right)\right]$$

- **The new snow falling has density depending on temperature and wind**

$$\rho_{sn,fresh} = \max\left(\rho_{sn,fresh}^{\min}, a_{\rho sn} + b_{\rho sn}\left(T_{air} - Tf\right) + c_{\rho sn}\left(V_{air}\right)^{1/2}\right)$$

Snow density: evolution on ground

$$\frac{\partial D_{sn}}{\partial t} = c_r D_{sn}$$

$$c_r = -\left[\frac{1}{D_{sn}}\frac{\partial D_{sn}}{\partial t}\right]_{destructive} - \left[\frac{1}{D_{sn}}\frac{\partial D_{sn}}{\partial t}\right]_{overburden} - \left[\frac{1}{D_{sn}}\frac{\partial D_{sn}}{\partial t}\right]_{melting}$$

$$-\left[\frac{1}{D_{sn}}\frac{\partial D_{sn}}{\partial t}\right] = -c_D^A c_D^1 c_D^2 \exp\left[-c_D^B\left(T_f - T_{sn}\right)\right]$$

$$c_D^1 = c_D^2 = 1$$

$$\rho_{sn}^{solid} > 100\,\mathrm{kg\ m^{-3}}$$

$$c_D^1 = \exp\left[0.046\left(\rho_{sn}^s - 100\right)\right]$$

$$\rho_{sn}^{liquid} > 0.01\,\mathrm{kg\ m^{-3}}$$

$$c_D^2 = 2$$

$$-\left[\frac{1}{D_{sn}}\frac{\partial D_{sn}}{\partial t}\right] = \frac{1}{\Delta t}\left[\frac{f^{t+1} - f^t}{f^t}\right]$$

$$-\left[\frac{1}{D_{sn}}\frac{\partial D_{sn}}{\partial t}\right] = -\frac{1}{\Delta t}\left[\frac{\Delta t / L_f\, Q_{sn}^{INT}}{S - S_l}\right]$$

$$-\left[\frac{1}{D_{sn}}\frac{\partial D_{sn}}{\partial t}\right] = \frac{0.5S}{c_o^A}\exp\left[-c_o^B\left(T_f - T_{sn}\right) - c_o^C \rho_{sn}^s\right]$$

Forest-Snow Albedo

- **Albedo of Forest areas with snow underneath was fixed to 0.15 (quite dark). A MODIS-derived vegetation dependent albedo is used.**

Index	Vegetation type	Albedo
3	Evergreen needleleaf trees	0.27
4	Deciduous needleleaf trees	0.33
5	Deciduous broadleaf trees	0.31
6	Evergreen broadleaf trees	0.38
18	Mixed forest / woodland	0.29
19	Interrupted forest	0.29

Open-Area Snow Albedo

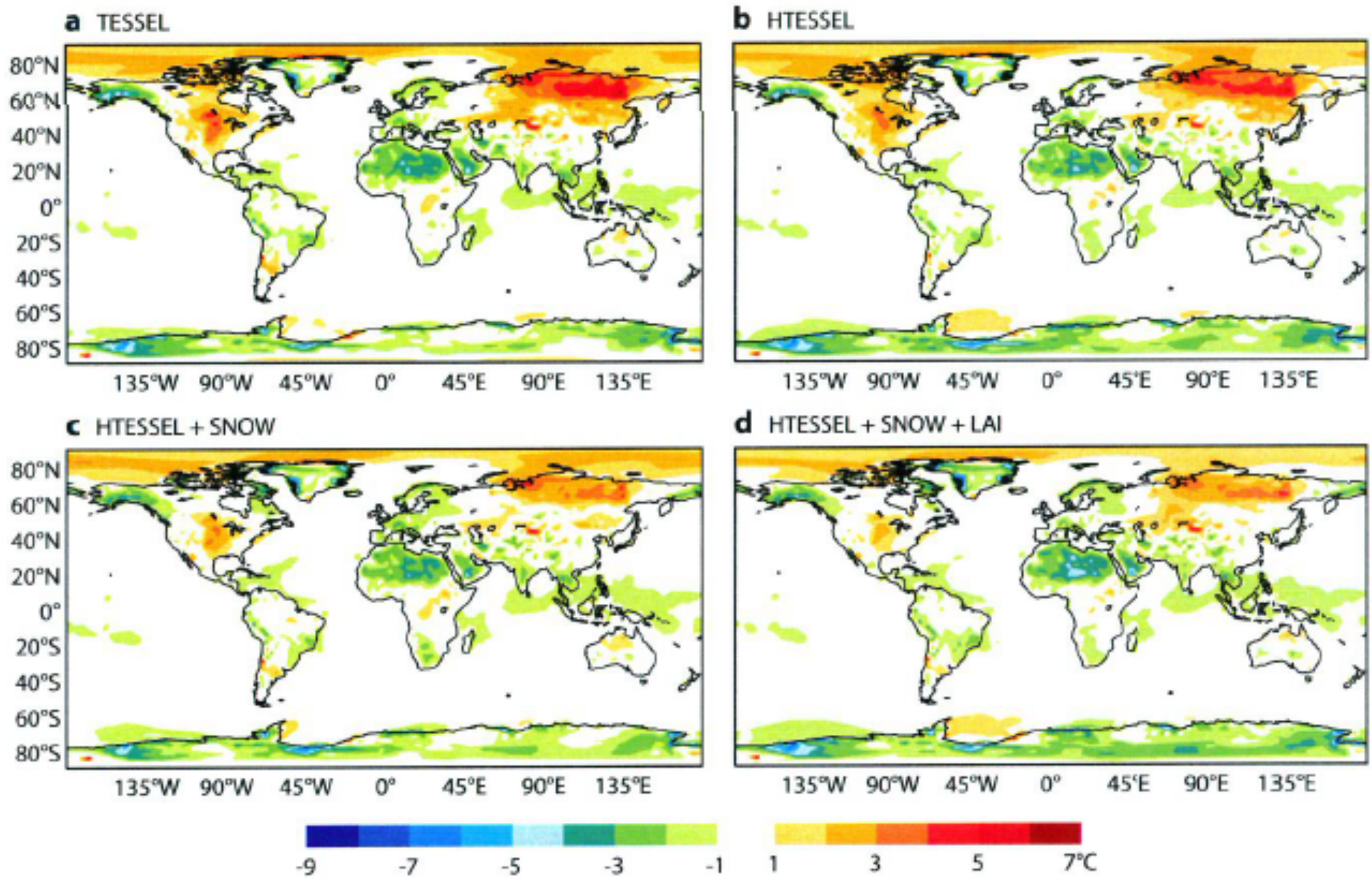
- **Open area albedo is aging from 0.85 in case of fresh snow to 0.5 for old snow, however in case of new snowfall the albedo was istantaneously re-whitened to 0.85, regardless of the snowfall amount.**

$$\alpha_{sn}^{t+1} = \begin{cases} \alpha_{sn}^{t} - \tau_a \, \Delta t / \tau_1 \\ \left(\alpha_{sn}^{t} - \alpha_{\min}\right) \exp\left(-\tau_f \, \Delta t / \tau_1\right) + \alpha_{\min}, \begin{cases} M_{sn} > 0 \\ \text{or} \\ T_{sn} \geq T_0 - 2 \end{cases} \end{cases}$$

$$\alpha_{sn}^{t+1} = \alpha_{sn}^{t+1} + \min\left(\frac{F \Delta t}{10}, 1\right)\left(\alpha_{\max} - \alpha_{sn}^{t+1}\right)$$

Climate impact

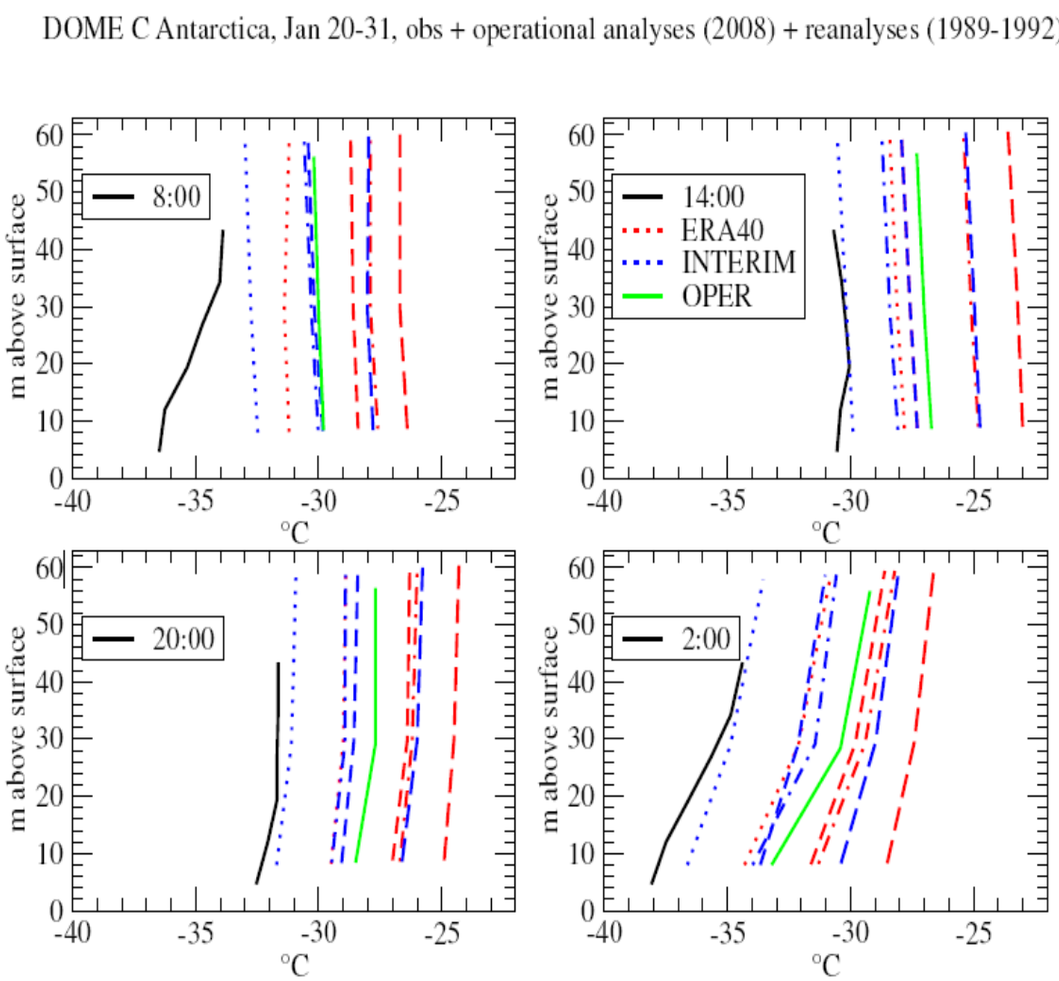
Hindcasts, 4-member 13-month temperature difference



simulations colder than ERA-Interim **Warmer than ERA-Interim**

Motivations of snow albedo revision

- **A large bias in temperature and wind at DOME Concordia**



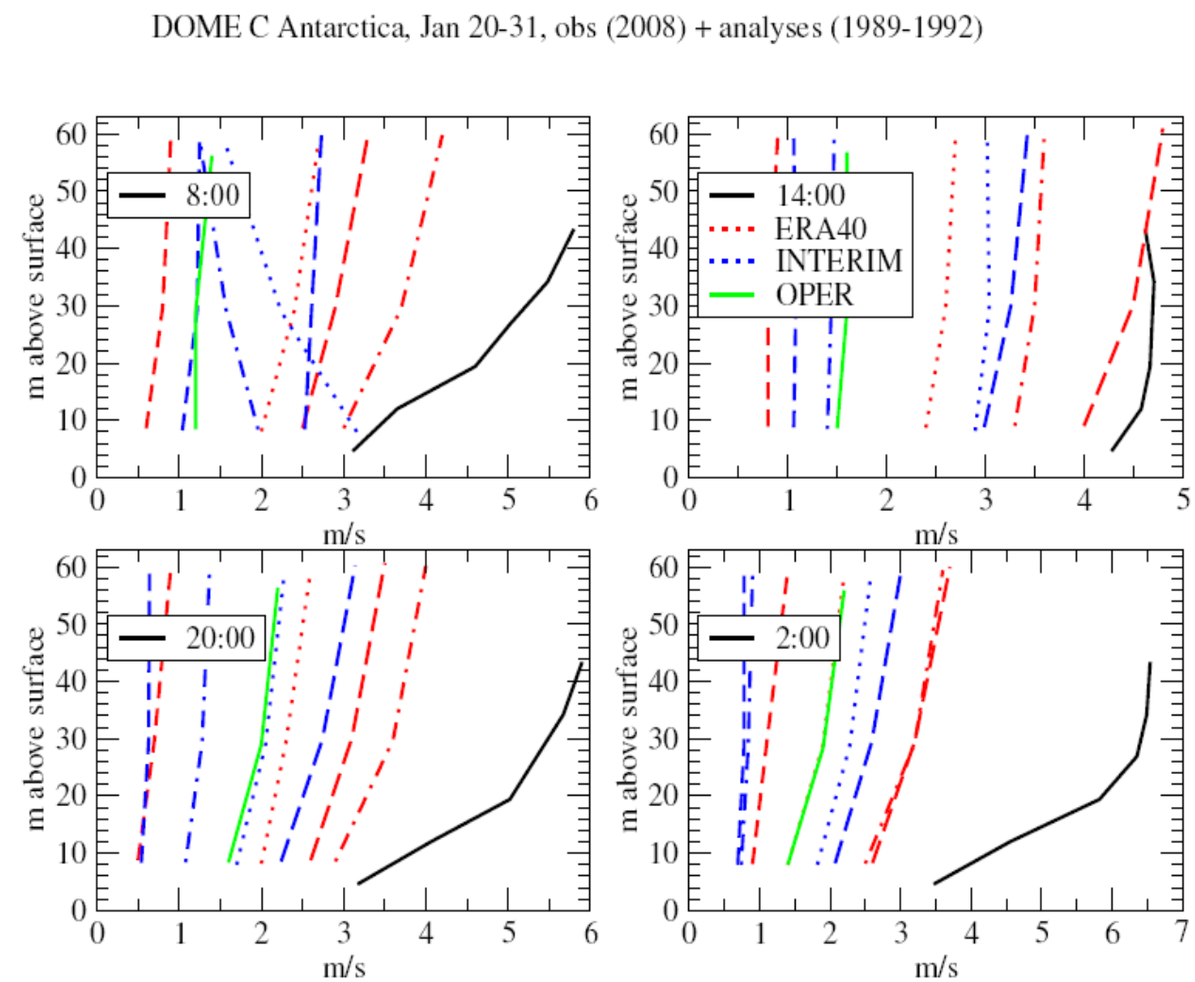


Figure 1: Temperature profile: tower observations (black), OPER analysis (green), ERA-40 (red, Interim (blue, 1989-1992). Courtesy of C. Genthon.

Figure 2: Wind profile. As in Fig. 1.

Antarctica snow studies

- **Although diurnal variations of albedo are present, indication that an albedo of 0.8 is applicable over Antarctica is provided by Pirrazzini (2004).**
- **This means a 5% increase in albedo from the operational setup.**
- **Idealized green-house models (2-layers) indicate that a 5% albedo change could lead to roughly 4 K on surface temperature (F.W. Taylor, 2005, Elementary climate physics, Oxford University press).**

PIRAZZINI: SURFACE ALBEDO OVER ANTARCTICA

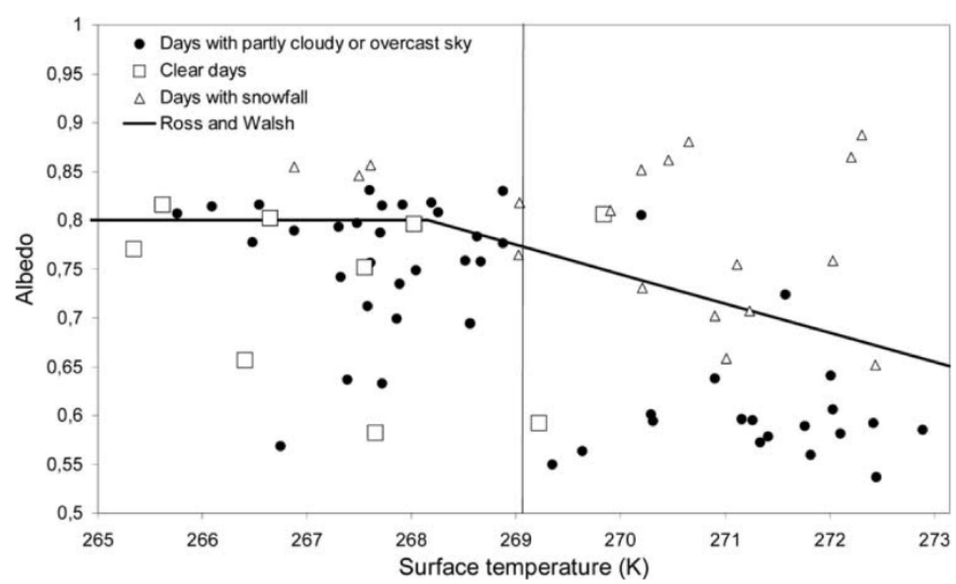


Figure 5. Daily mean surface albedo versus daily mean surface temperature at Hells Gate. The line represents the Ross and Walsh parameterization of snow albedo over the Arctic.

Long integration (observed SSTs)

- **Sensitivity experiments show a largely localized impact on Antarctica**

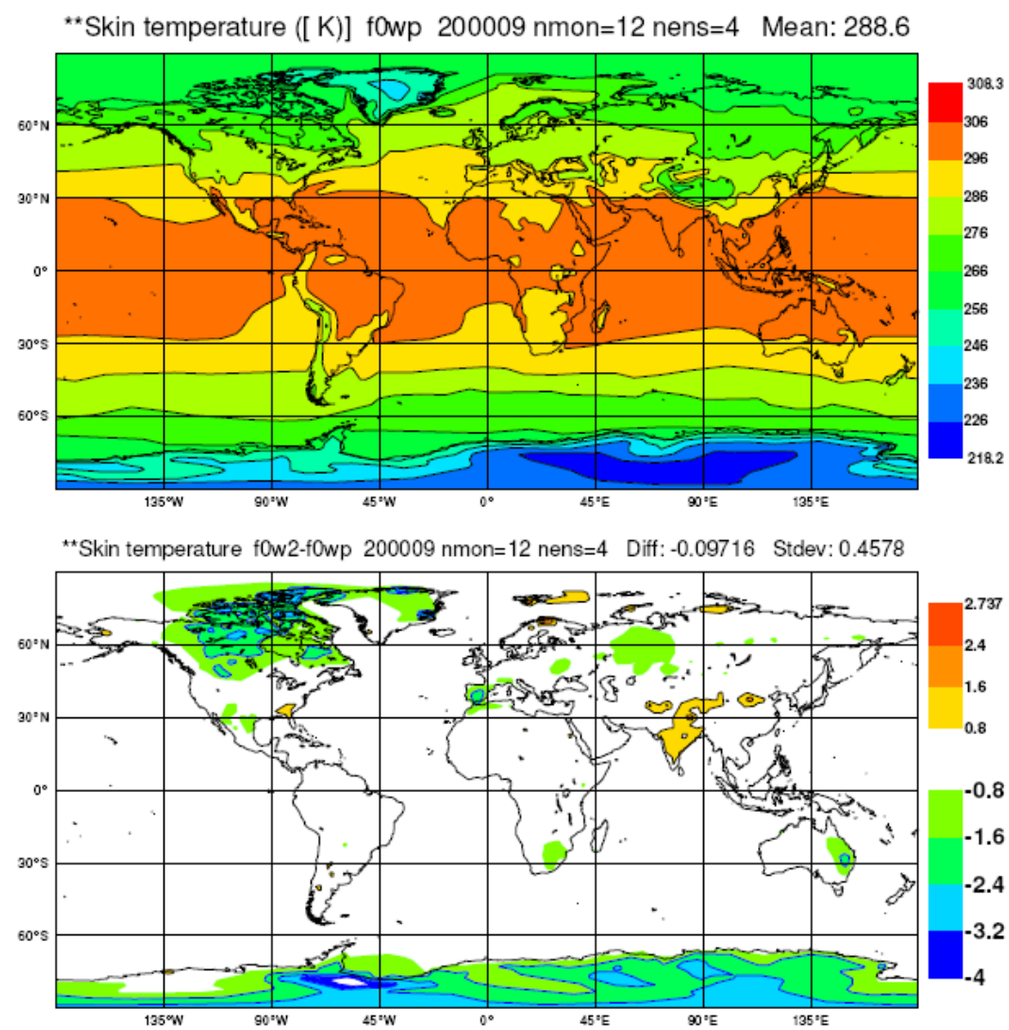
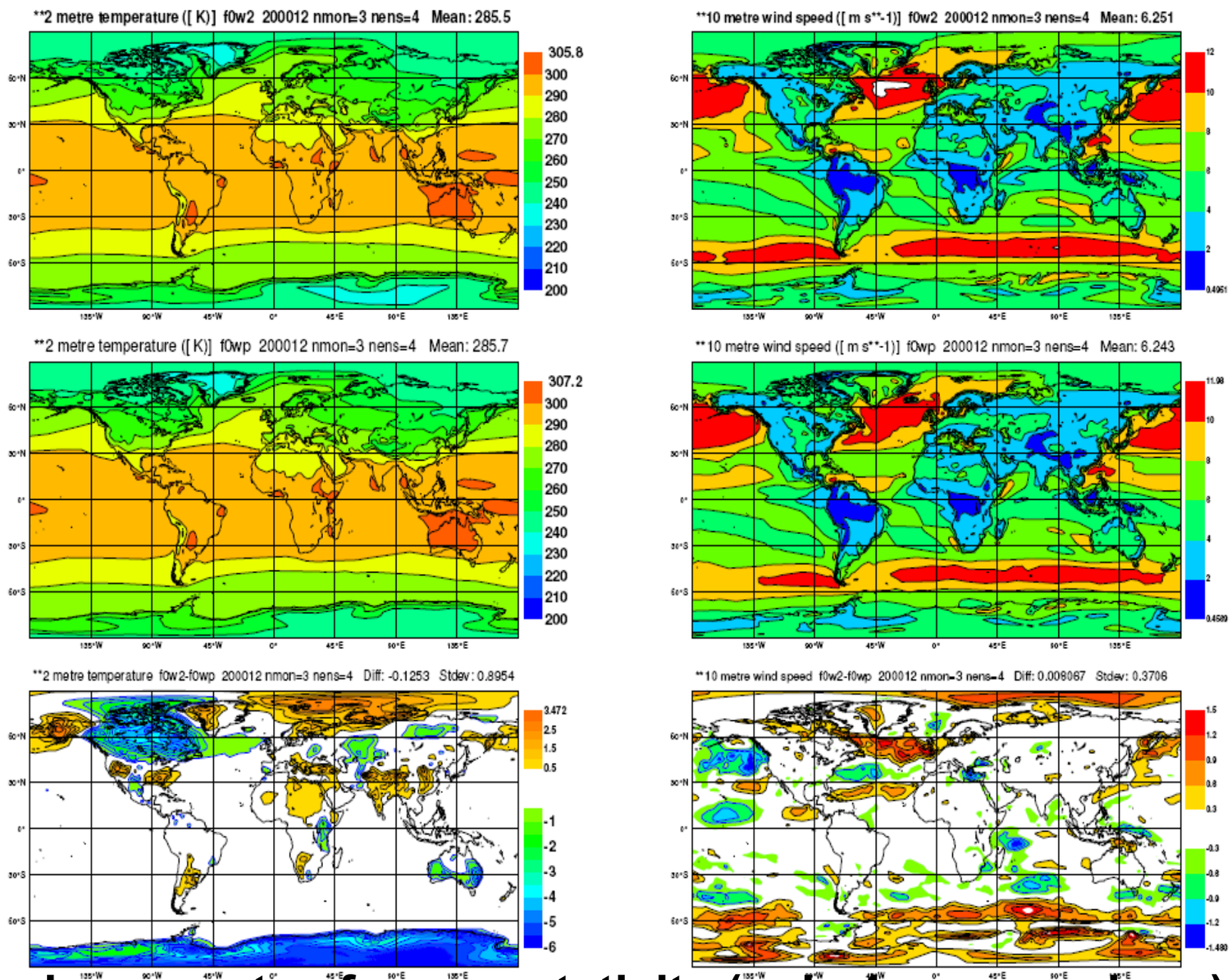


Figure 3: Impact of increased albedo in annual mean skin temperature.

Austral summer impact

2m temperature (4-6 K reduction) and wind (2-4 m/s increase) are affected



Under caveats of repesentativity (only 4 ens members)

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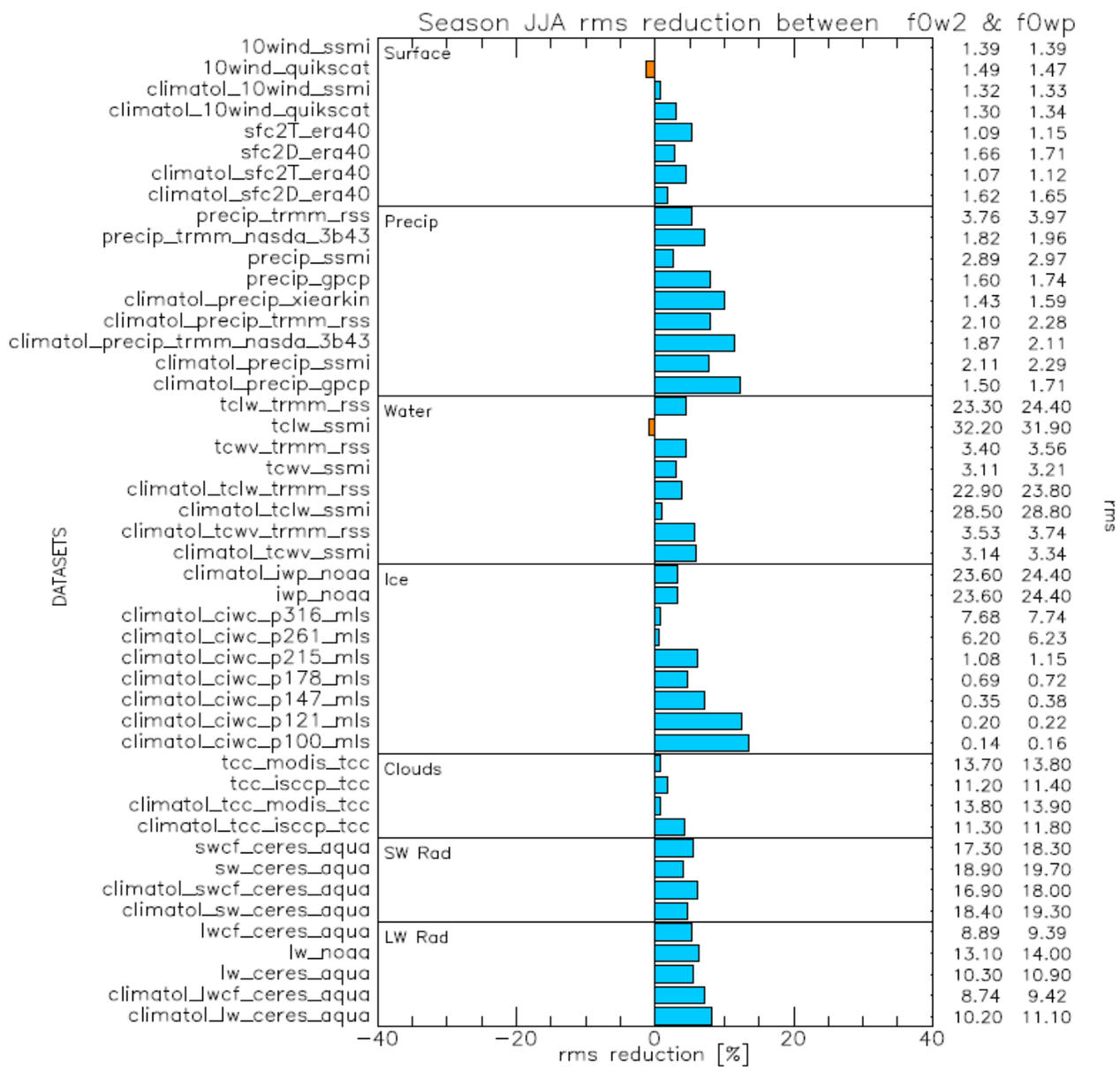
Figure 5: Impact of increased albedo in DJF 2m temperature (left) and 10m wind (right).

Overall climate impact

- **At the end of a "climate experiment" (13-month FC with specified SSTs) the verification indicates improvements in all the datasets used.**



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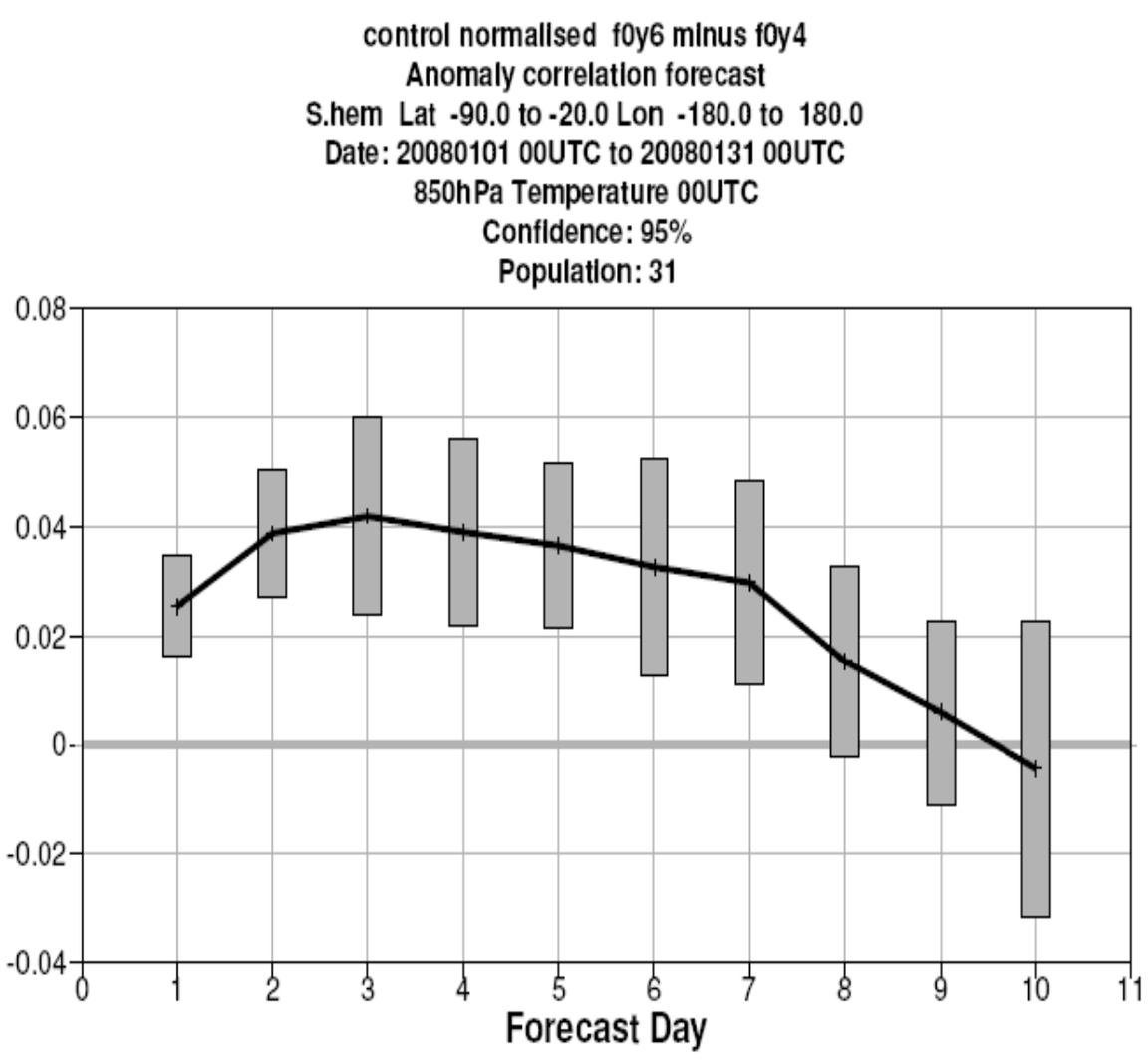
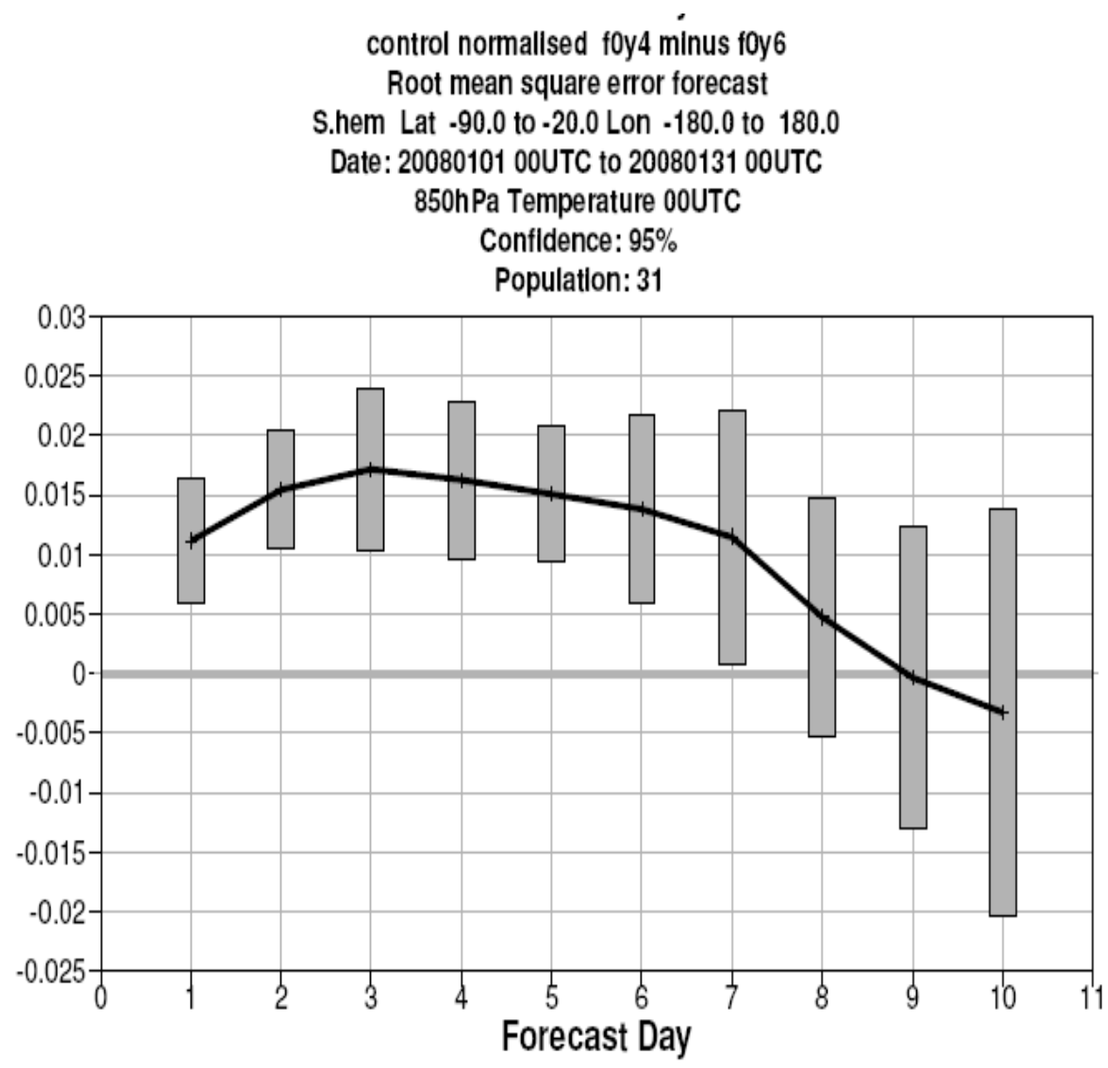
Forecasts impact

- **A set of 31 forecast of 10-days (Jan '08) shows T850hPa improvements in SH up to 4% in ACC (1.5% in RMSE) and significant up to 7-days**





Circulation impact on Antarctica

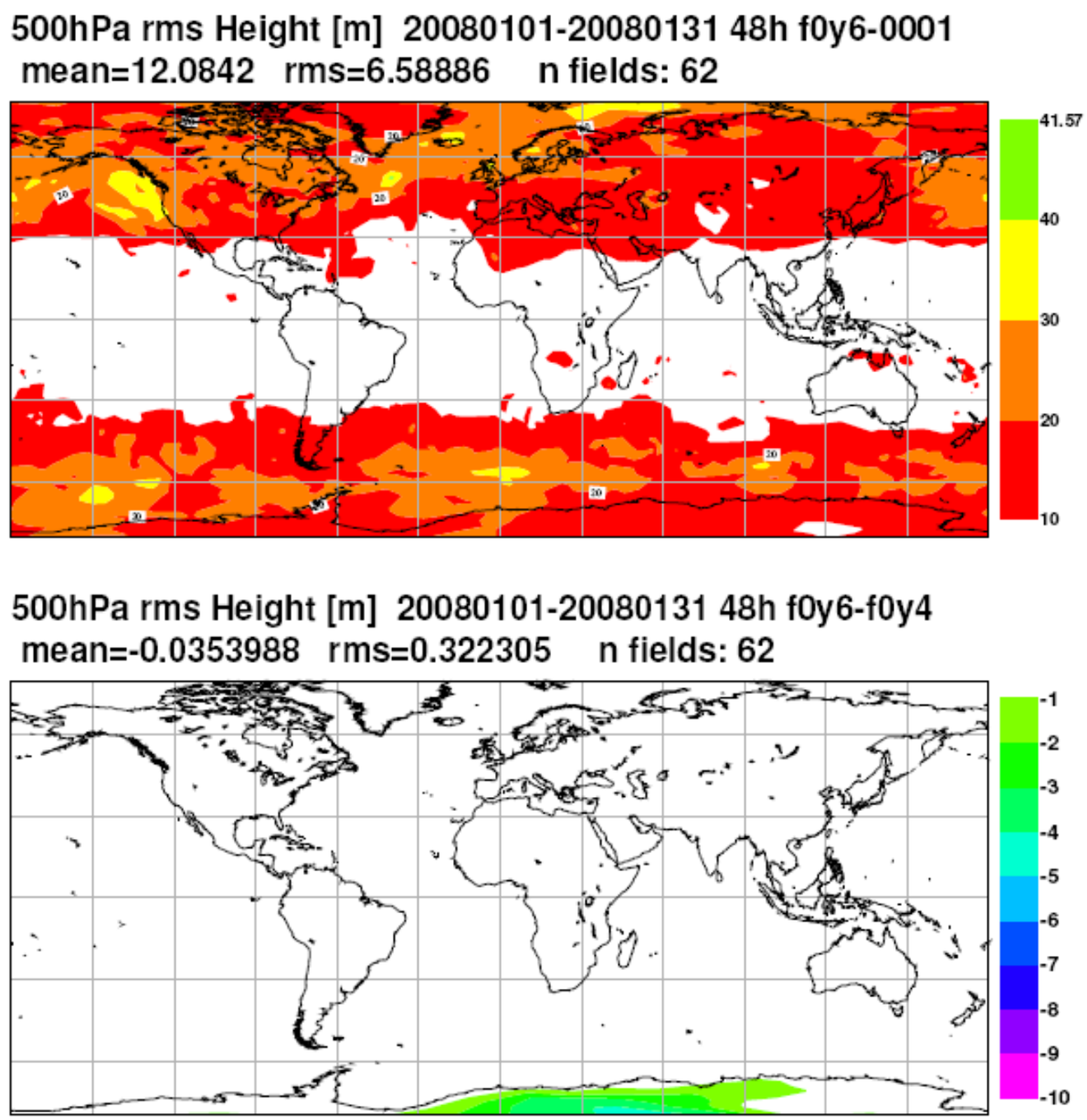


Figure 9: Mean RMSE difference (albedo Exp. − control CY33R1) for 500 hPa geopotential heigth (48-hour forecast) for January 2008, evaluated against the operational analysis.

Impact on atmospheric T profile

- **Atmospheric profile responds to albedo whitening with a cooling very effective at the surface (here evaluated on a 48-h forecast).**

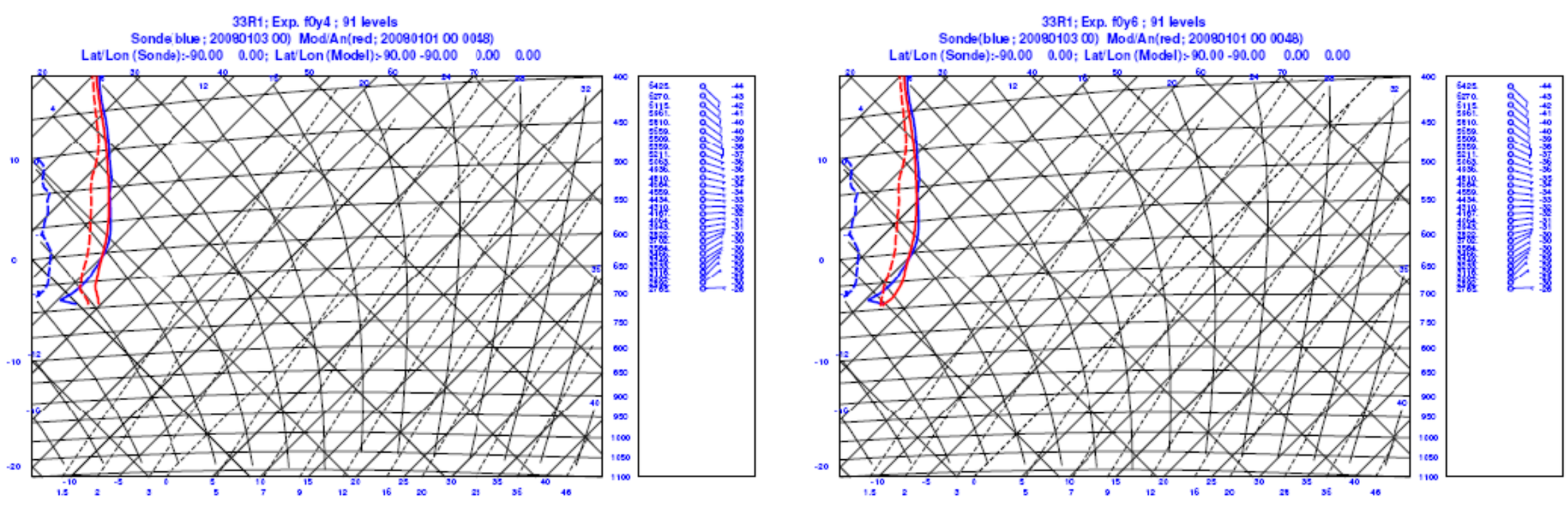


Figure 10: Averaged sounde profile for the South Pole station for January 2008 (blue) compared with averaged 48-hour forecasts (red): CY33R1 control (left) and increased permanent snow albedo experiment (right).

Conclusions

- **A new snow scheme has been implemented in the IFS with large positive impact on temperature in NH but is not activated over Antarctica**
- **A simple albedo retuning for Antarctica has proven to be an effective constraint to model bias**
- **Impact is visible throughout the forecast range and in long integrations.**
- **The albedo change corrects the mean daily temperature (but there are still problems with diurnal cycle due to simple treatment of glaciers).**
- **Activation of the new scheme (albedo&density?lower thickness of the thermally active layer?) may improve some aspects of the diurnal cycle (under testing)**
- **Future revision of the snow scheme may improve on the diurnal cycle (multiple vertical layers allowing to resolve diurnal cycle variations).**
- **Unification of snow modelling is a long-term target for treatment of surface processes over sea-ice, glaciers, non-permanent snow.**