Parameterisation of Lake and Sea Ice in the NWP Models of the German Weather Service

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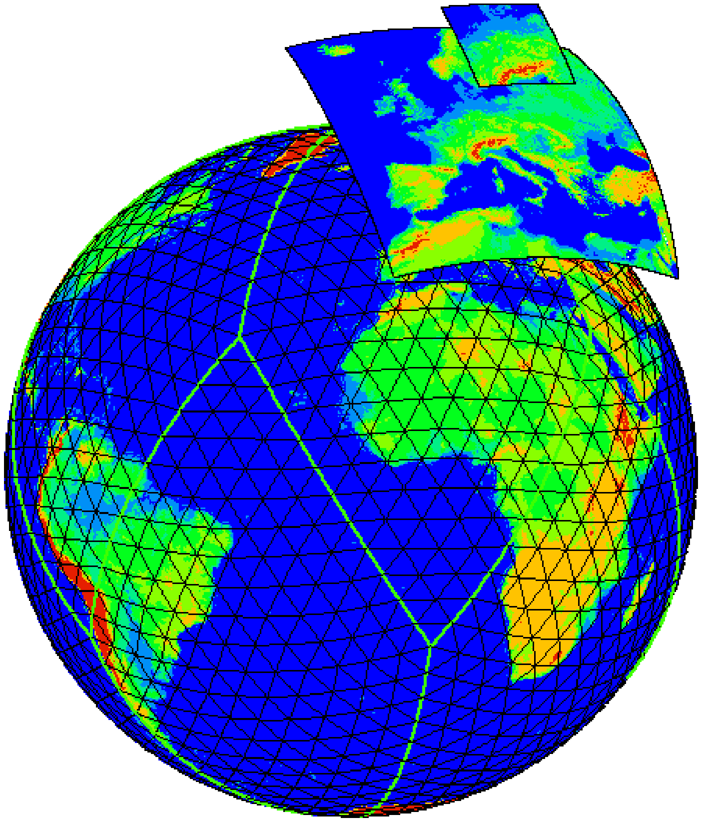
Outline

- ➔NWP model suite of DWD
- ➔Bulk models (parameterisation schemes) – basic idea
- ➔Lake ice vs. sea ice, interaction of ice thermodynamic model with data assimilation scheme
- ➔Single-column tests
- ➔Performance of sea and lake ice schemes within NWP models GME and COSMO
- ➔Conclusions and outlook

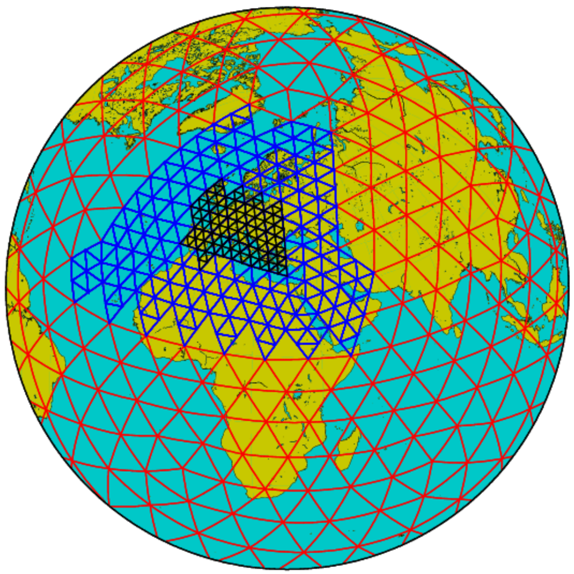
NWP Model Suite of DWD

- **GME** (Majewski et al. 2002): global, hydrostatic, icosahedral-hexagonal grid, horizontal mesh size ~30 km, thermodynamic sea ice model (Mironov and Ritter 2004) used operationally
- **COSMO-EU** (Steppeler et al. 2003, http://www.cosmo-model.org): limited-area, non-hydrostatic (fully compressible), rotated lat-lon grid, horizontal mesh size ~7 km, parameterisation (mass-flux) scheme of deep precipitating convection, lake model FLake (Mironov 2008, Mironov et al. 2010, http://lakemodel.net) including parameterisation of lake ice tested pre-operationally
- **COSMO-DE** (Baldauf et al. 2010, http://www.cosmo-model.org): limited-area, non-hydrostatic (fully compressible), rotated lat-lon grid, horizontal mesh size ~2.8 km, no parameterisation scheme of deep precipitating convection, no sea/lake ice scheme so far
- **ICON** (being developed by DWD and MPI): global, non-hydrostatic, icosahedral-triangular grid, local mesh refinement (horizontal mesh size from ~20 km to ~5 km in the focus area), both sea ice scheme and FLake will be implemented

NWP Model Suite of DWD (cont'd)



GME, COSMO-EU, COSMO-DE
(colours show orography)



ICON

Bulk Ice Models – Basic Idea

Based on the idea of self-similarity (assumed shape) of the temperature-depth curve. Using ice surface temperature $\theta_i(t)$ and ice thickness $h_i(t)$ as appropriate scales of temperature and depth, the temperature profile within the ice layer is represented as

$$\theta(z,t) = \theta_f + [\theta_i(t) - \theta_f]\Phi(\varsigma), \quad \varsigma = z / h_i(t)$$

A "universal" function $\Phi(\zeta)$ satisfies the boundary condition is $\Phi(0)=0$ and $\Phi(1)=1$ (the z-axis is directed upward with the origin at the lower surface of the ice).

Analogy to the Mixed-Layer Concept

Using $\theta_s(t)$ and $h(t)$ as appropriate scales of temperature and depth, the temperature profile in the upper mixed layer is represented as

$$\frac{\theta(z,t)}{\theta_s(t)} = \Phi(\xi), \quad \xi = \frac{z}{h(t)}.$$

Since the layer is well mixed, the "universal" function $\Phi(\xi)$ is simply a constant equal to 1.

Then, integrating the heat transfer equation (partial differential equation in z, t)

$$\frac{\partial \overline{\theta}}{\partial t} = -\frac{\partial \overline{w'\theta'}}{\partial z}$$

over z from 0 to $h(t)$, reduces the problem to the solution of an ordinary differential equation for $\theta_s(t)$,

$$\frac{d\theta_s}{dt} = \frac{Q_s - Q(h)}{h}.$$

Bulk Lake/Sea Model – Summary

... Integrating the heat transfer equation (partial differential equation) with due regard for the self-similar representation of $\theta_s(z,t)$ and rearranging ... we get the system of ordinary differential equations for time-dependent ***parameters*** that specify the temperature profile, viz., $\theta_i(t)$ and $h_i(t)$, where **θ_i is a major concern**.

In the regime of ice growth (and/or melting from below for sea ice)

- equations for $h_i(t)$ and $\theta_i(t)$

In the regime of ice melting from above

- equation for $h_i(t)$, and θ_i is constant equal to the θ_{f0} (fresh-water freezing point)

NB: The model does not require re-tuning and

is computationally very inexpensive (vitally important for NWP!)

Lake Ice vs. Sea Ice
Interaction with Data Assimilation Scheme

Lake ice (ice module of the fresh-water lake model Flake)

- thermodynamic ice model carries equations for $h_i(t)$ and $\theta_i(t)$ and can produces new ice (lakes are allowed to freeze up themselves in response to atmospheric forcing)
- no observational data are assimilated at present

Sea ice

- thermodynamic ice model carries equations for $h_i(t)$ and $\theta_i(t)$ but creates no new ice (ocean is not allowed to freeze up itself)
- horizontal distribution of sea ice is subordinate to data assimilation scheme that delivers ice fraction f_i for each atmospheric-model grid box
- no ice if f_i is small (remove leftover as needed), h_i and θ_i are initialised with ad hoc values if there was no ice but data indicate it is present

Old GME sea ice scheme

- "climatological" values of θ_i if observational data indicate ice fraction in excess of 0.5

Single-Column Tests

- Lake Pääjärvi, Finland (61 N, depth = 15 m)
- Ryan Lake, USA (45 N, depth = 9 m)

Forcing in single-column mode

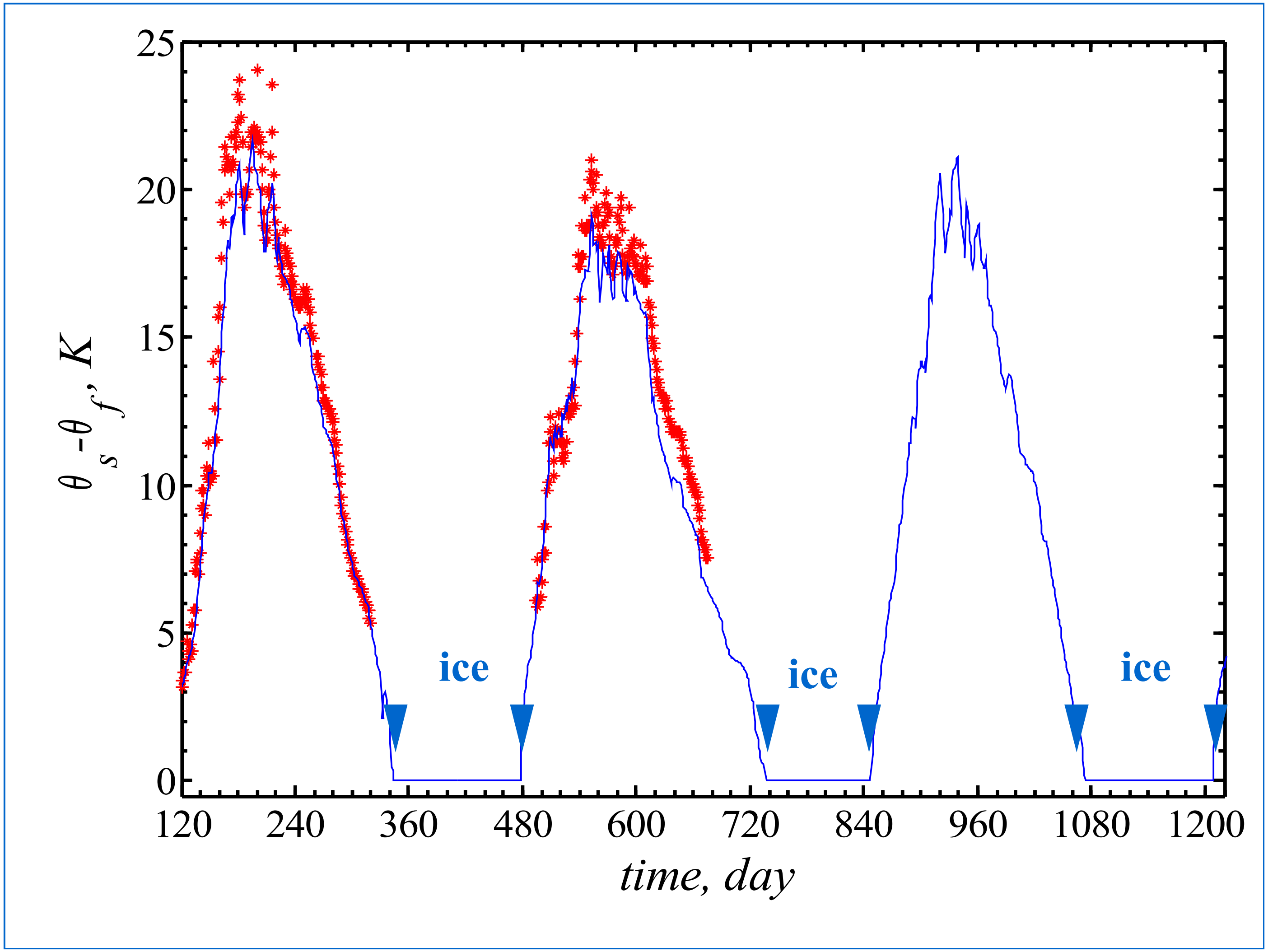
Known from observations:

- short-wave radiation flux,
- long-wave radiation flux from the atmosphere.

Computed as part of the solution (depend on lake surface temperature):

- long-wave downward radiation flux from the surface,
- fluxes of momentum and of sensible and latent heat,
- for ice-covered lakes, surface albedo.

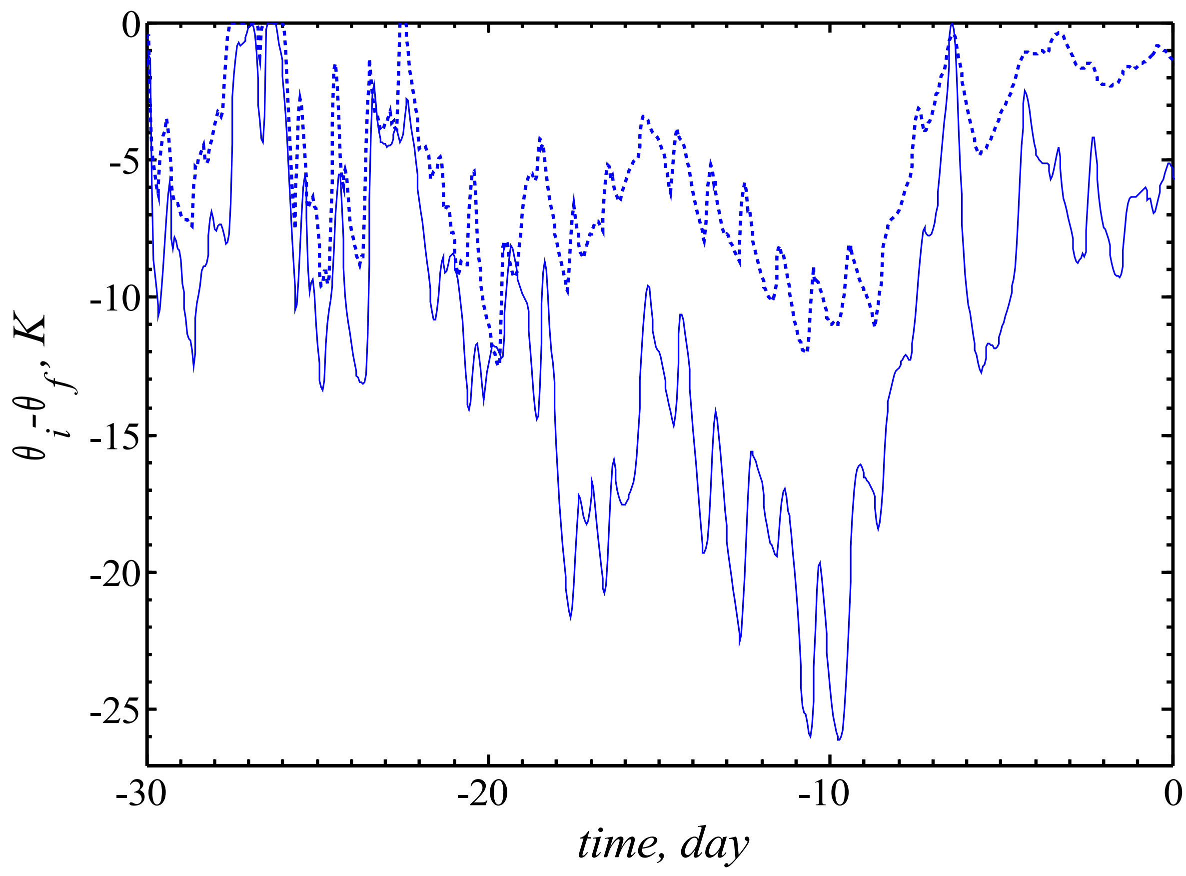
Lake Pääjärvi, 1 May 1999 - 31 August 2002



Water surface temperature θ_s (θ_f is the fresh-water freezing point)

Dots – measured, line - computed

Lake Ryan, December 1989



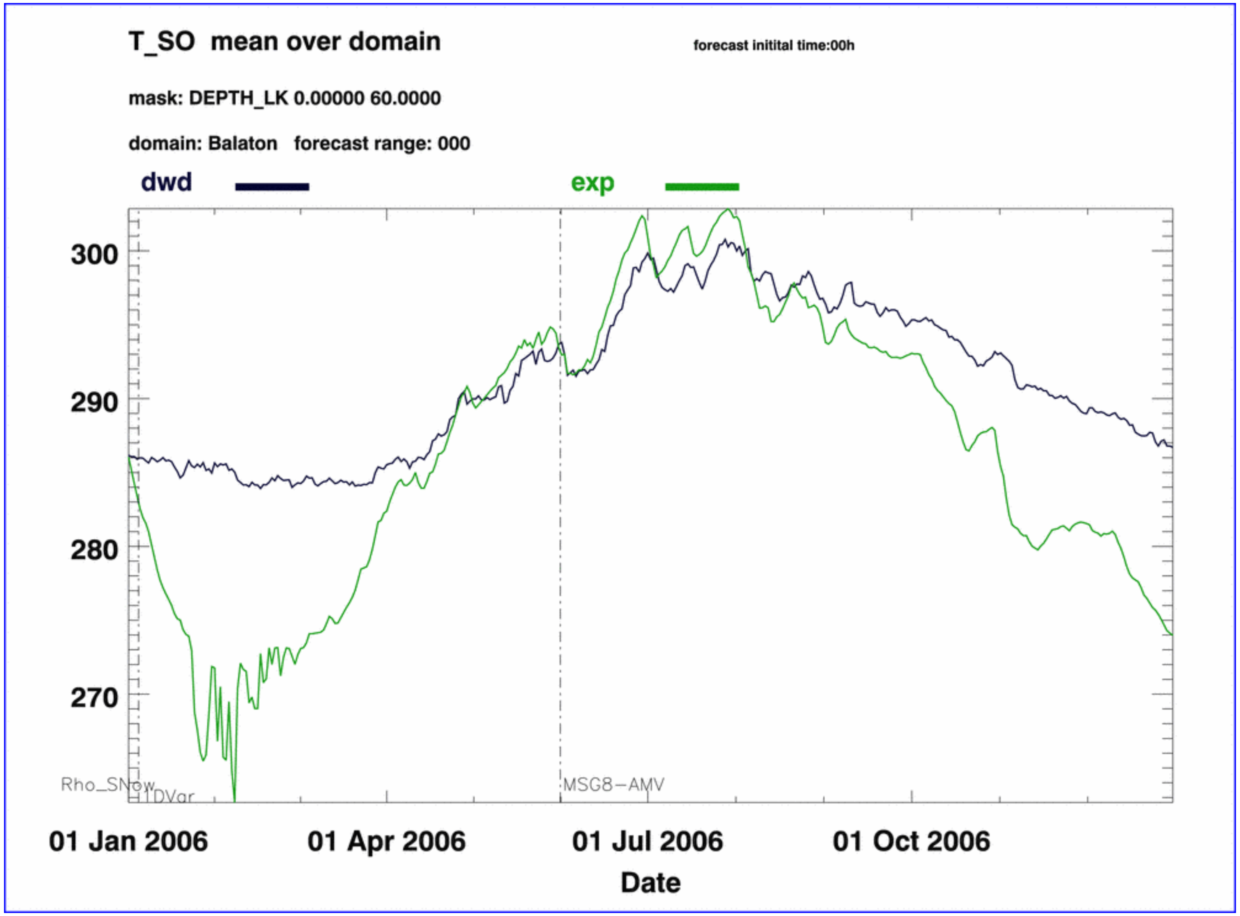
- Solid - modelled ice surface temperature
- Dotted - temperature measured with the uppermost sensor

Performance of COSMO Lake Ice Scheme (Ice Module of FLake)

Parallel Experiment

- Lakes are the COSMO-model grid-boxes with FR_LAKE>0.5, otherwise land or sea water (no tile approach)
- 2D fields of lake fraction and of lake depth (limited by 50 m), default values of other lake-specific parameters
- COSMO-FLake parallel experiment (including the entire data assimilation cycle) over 1 year, 1 January through 31 December 2006
- "Artificial" initial conditions, where the lake surface temperature is equal to the COSMO-model SST from the assimilation
- Turbulent fluxes are computed with the COSMO-model surface-layer scheme (Raschendorfer 2001); optionally, the new surface-layer scheme (Mironov et al. 2003, http://lakemodel.net) can be used
- The effect of snow is accounted for implicitly through the surface albedo

FLake in COSMO: Results from Parallel Experiment 5632
1 January – 31 December 2006



Lake Balaton, Hungary (mean depth = 3.3 m)

- Black – lake surface temperature from the COSMO SST analysis
- Green – lake surface temperature computed with FLake

FLake in COSMO: Results from Parallel Experiment 5632
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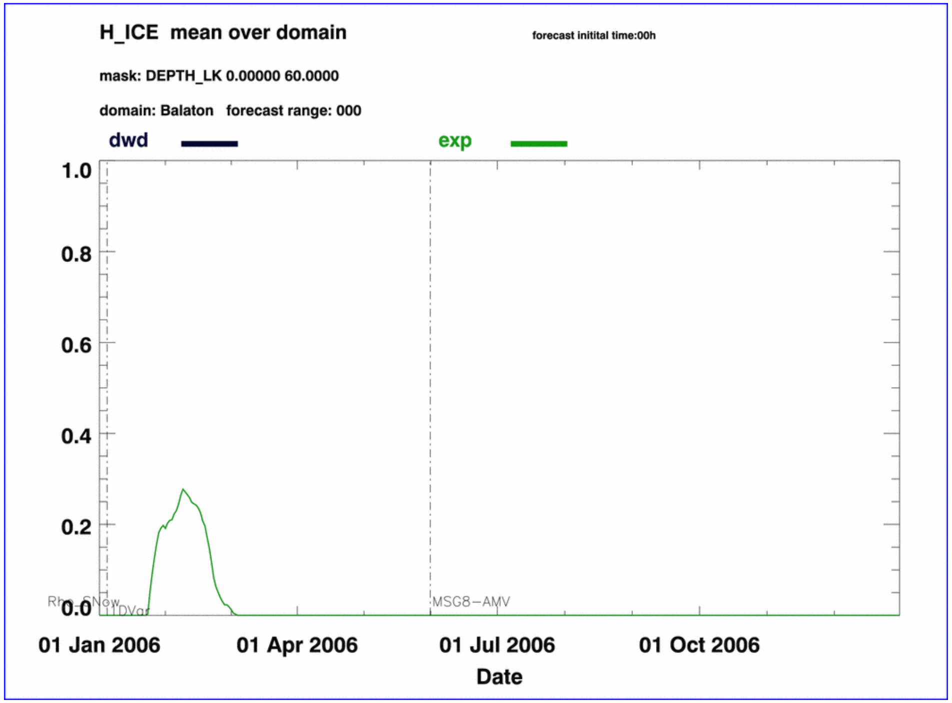

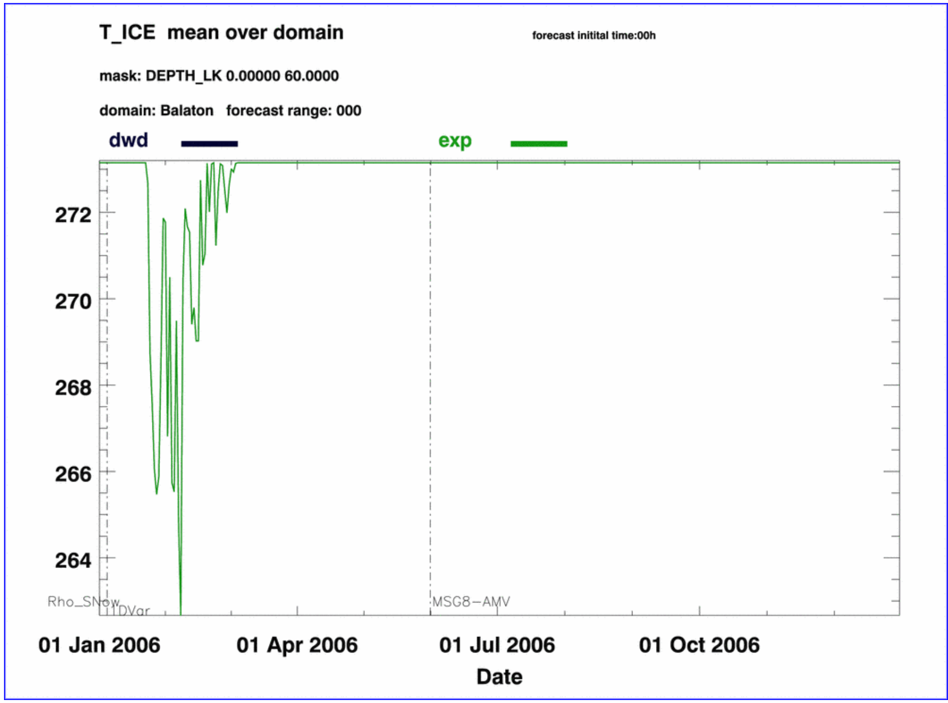

Lake Balaton, Hungary (mean depth = 3.3 m)

Ice thickness (left) and ice surface temperature (right) computed with FLake

FLake in COSMO: Results from Parallel Experiment 5632
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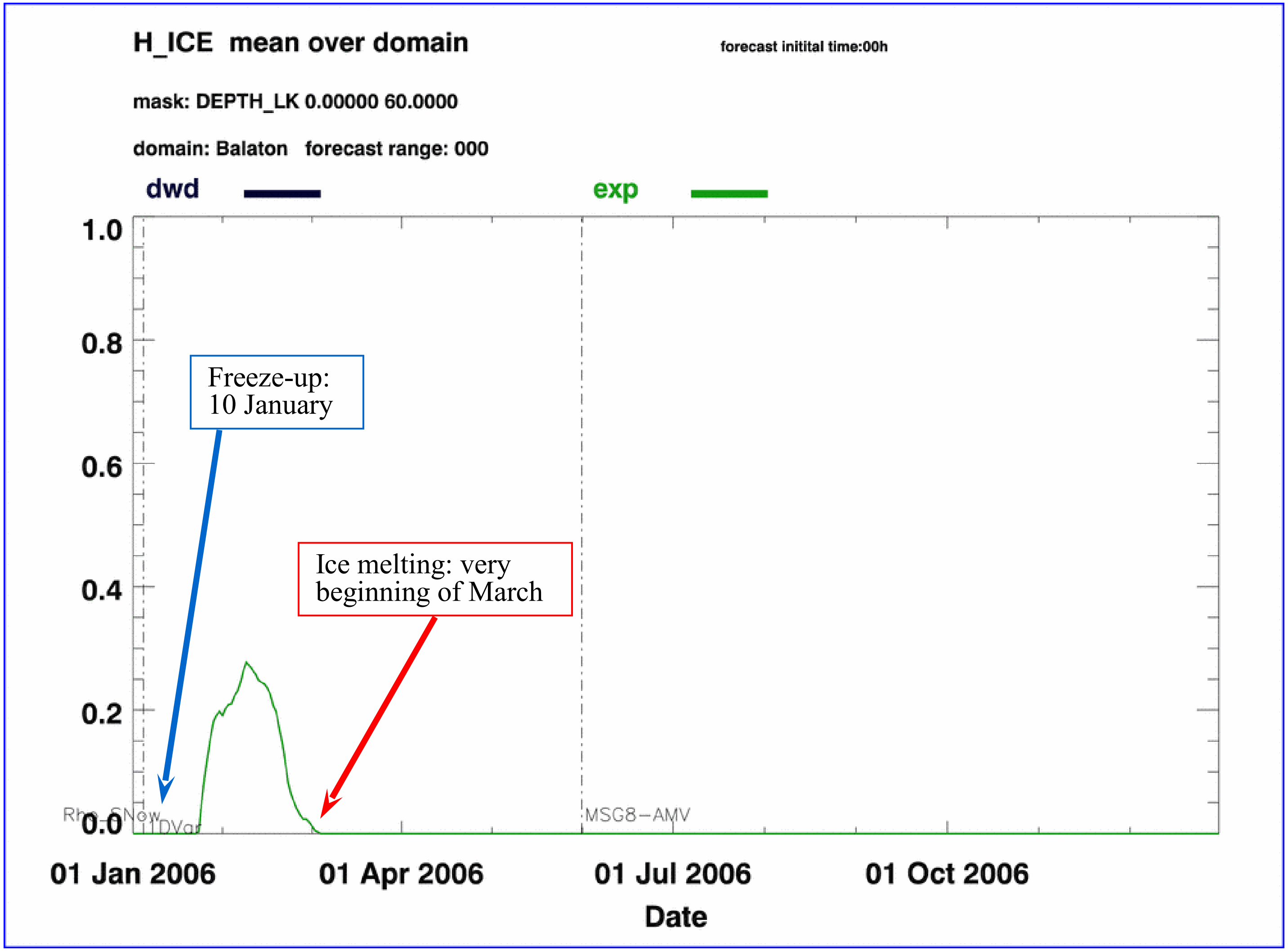
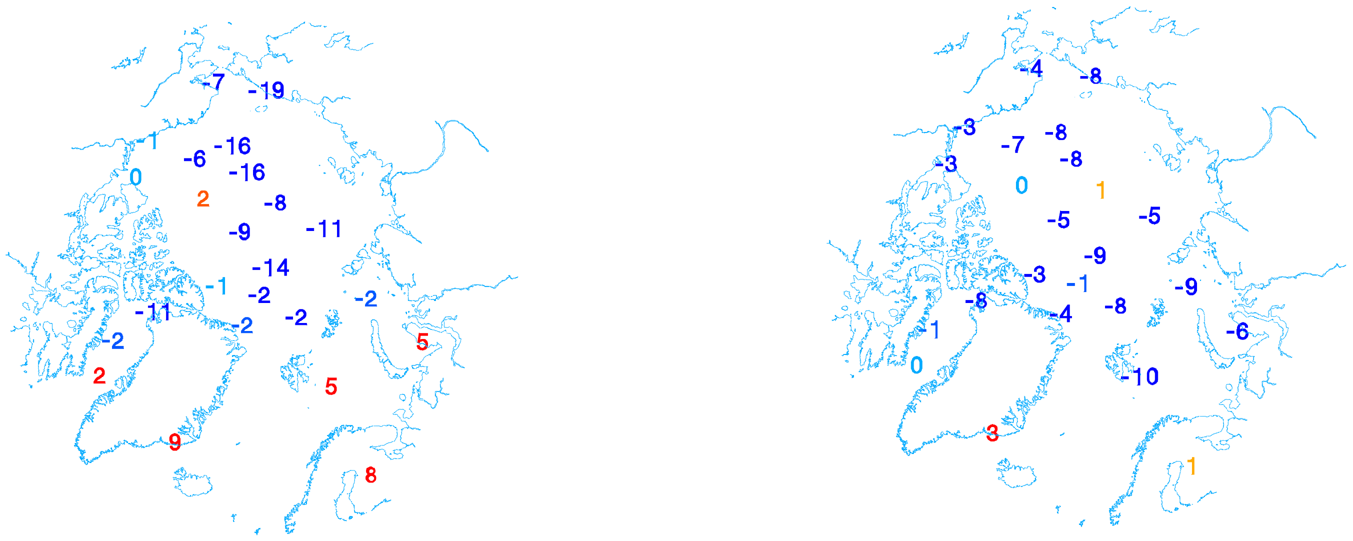


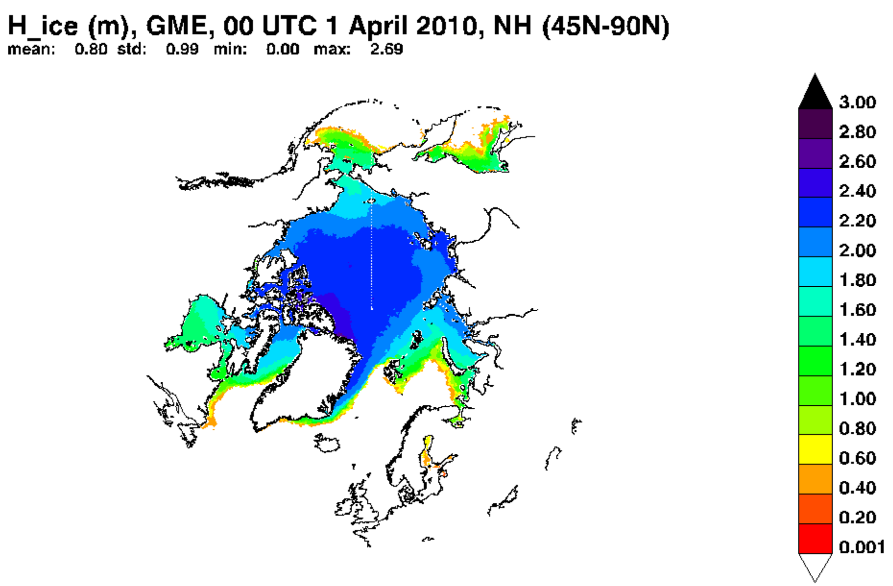
Lake Balaton, Hungary (mean depth = 3.3 m). Ice thickness computed with COSMO-FLake.

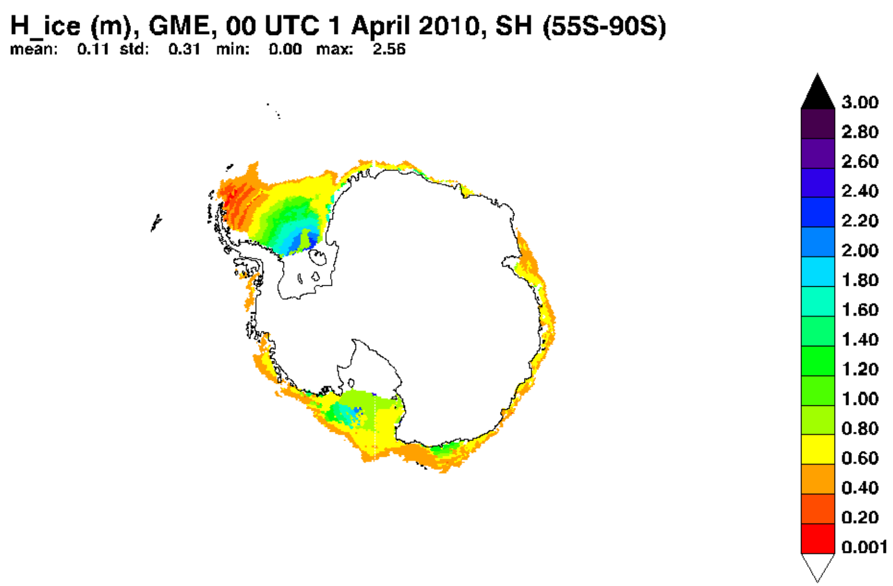
Performance of GME Sea Ice Scheme



The two-metre temperature in the Arctic at 12 UTC on 1 January 2004: left panel – GME analysis using the old sea ice scheme, right panel – GME analysis using the new sea ice scheme. Numbers show computed minus observed two-metre temperature difference (in K).

Performance of GME Sea Ice Scheme (cont'd)

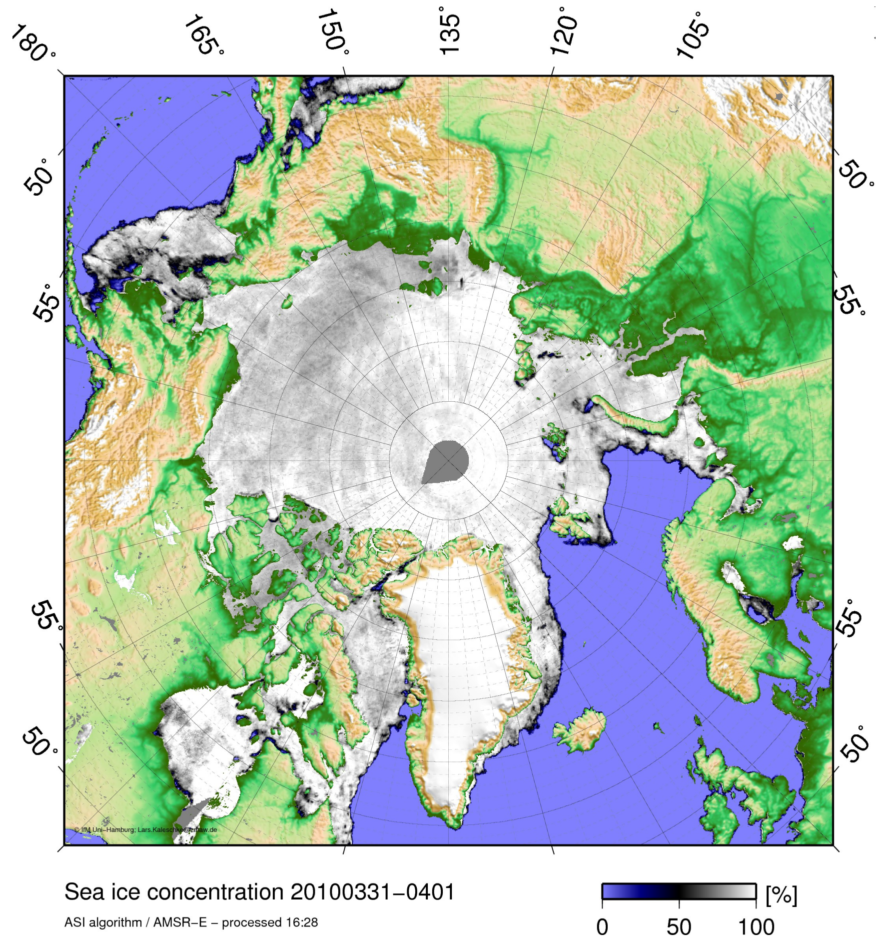


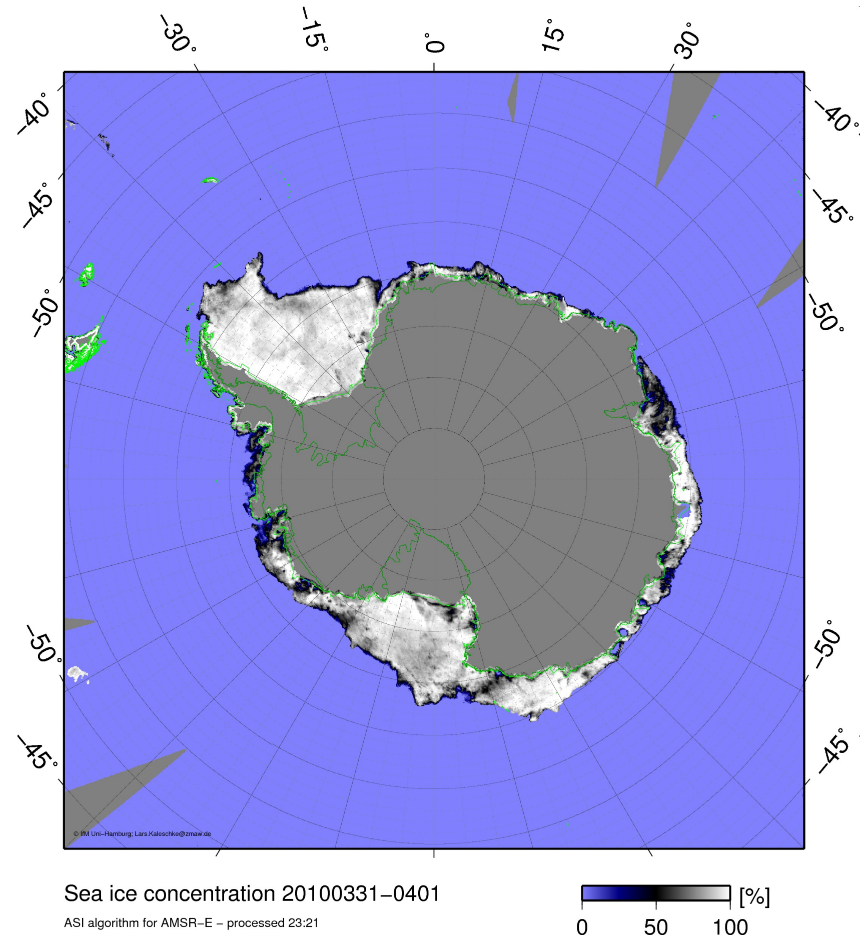


Ice thickness (m) from GME, 00 UTC 1 April 2010.

Left panel – Arctic, right panel – Antarctic.

Performance of GME Sea Ice Scheme (cont'd)



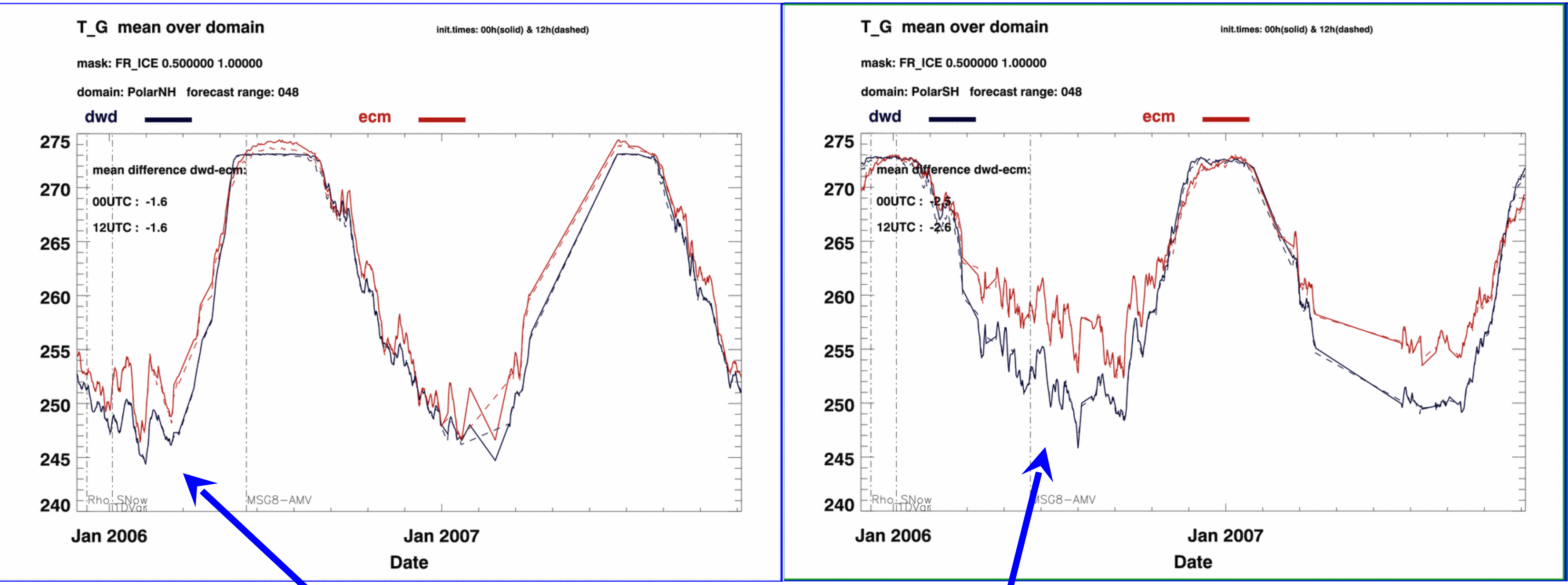


Ice concentration from observations, 1 April 2010.

Left panel – Arctic, right panel – Antarctic.

(http://www.ifm.zmaw.de/forschung/fernerkundung/meereis/amsre-sea-ice/)

Performance of GME Sea Ice Scheme (cont'd)



GME seems to be too cold

Ice surface temperature from 48h forecasts of GME (**black**) and of IFS ECMWF (**brown**). Left panel – Arctic, right panel – Antarctic.

IFS ECMWF ice scheme: heat transfer equation is solved numerically using 4 levels within an ice slab of fixed depth (1.5 m)

Performance of GME Sea Ice Scheme (cont'd)

Surface heat budget

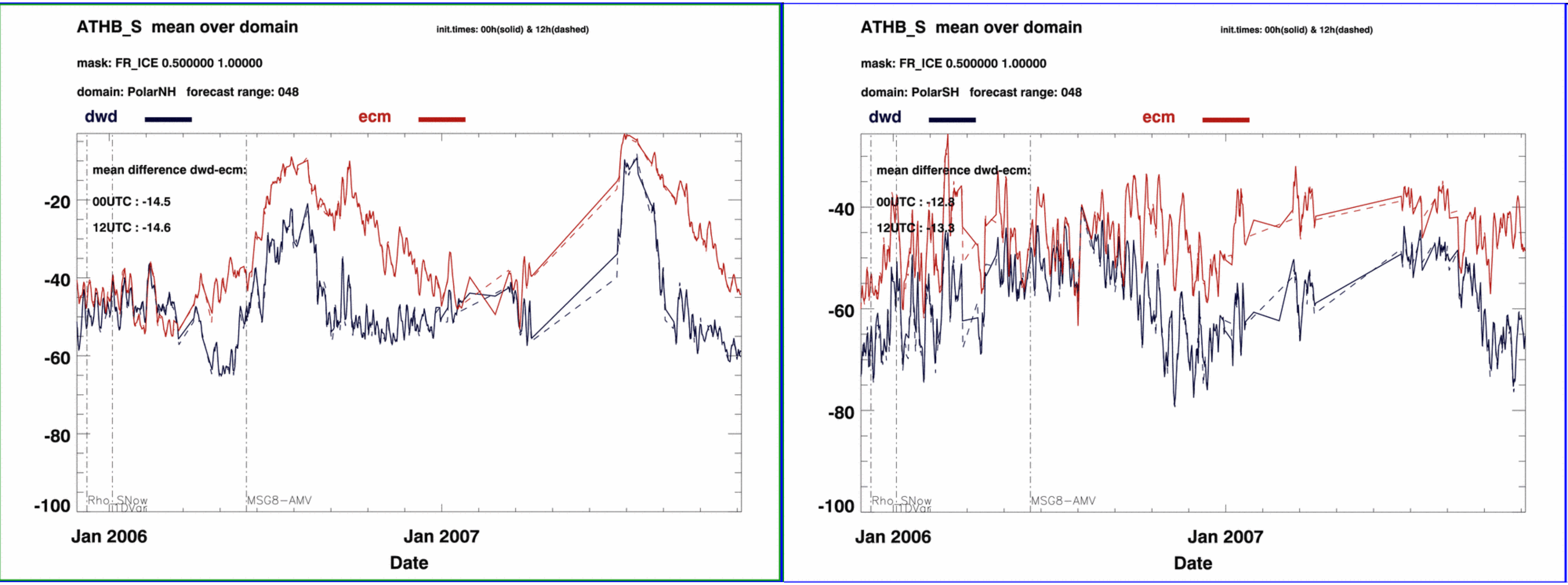
$$F_a + \varepsilon \sigma \theta_i^4 + \kappa_i \frac{\theta_i - \theta_f}{h_i} = 0$$

Using $\theta_f^4 \approx \theta_f^4 \left(1 + 4 \frac{\theta_i - \theta_f}{\theta_f} \right)$, we get

$$\theta_i = \theta_f - \frac{F_a + \varepsilon \sigma \theta_f^4}{(\kappa_i / h_i) + 4 \varepsilon \sigma \theta_f^3}$$

Taking σ=5.67·10^{-8} J/(m^2 s K^4), ε=0.99, κ_i =2.29 J/(m s K), θ_f=272 K and h_i=1.5 m, we find that **20 W/m^2 difference in F_a** (–190 W/m^2 vs. –210 W/m^2) **results in 4 K difference in θ_i** (253 K vs. of 257 K).

Performance of GME Sea Ice Scheme (cont'd)

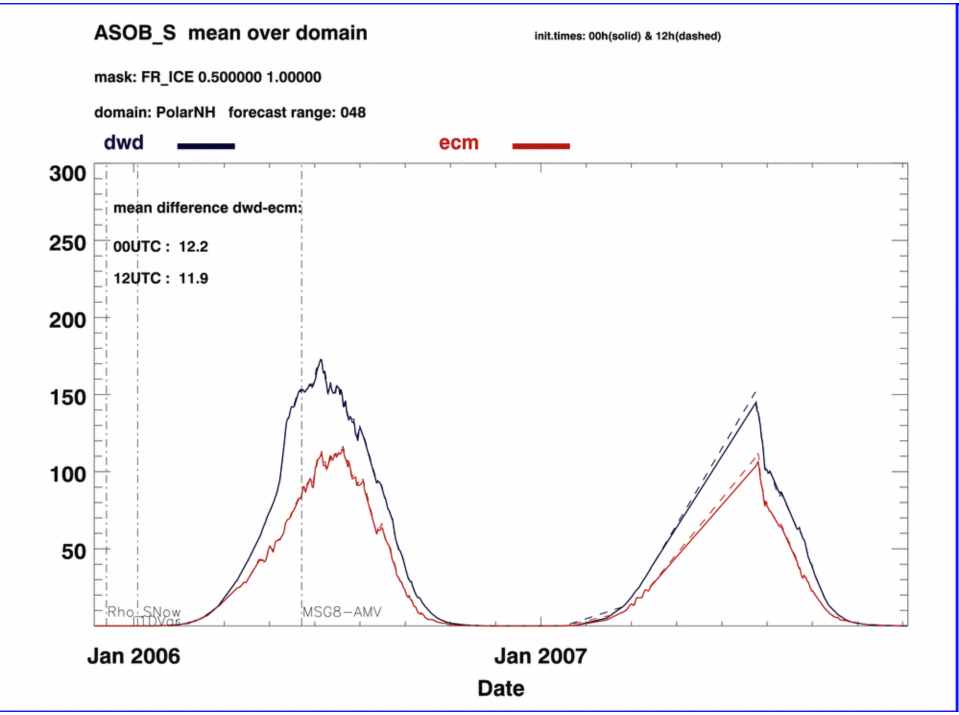


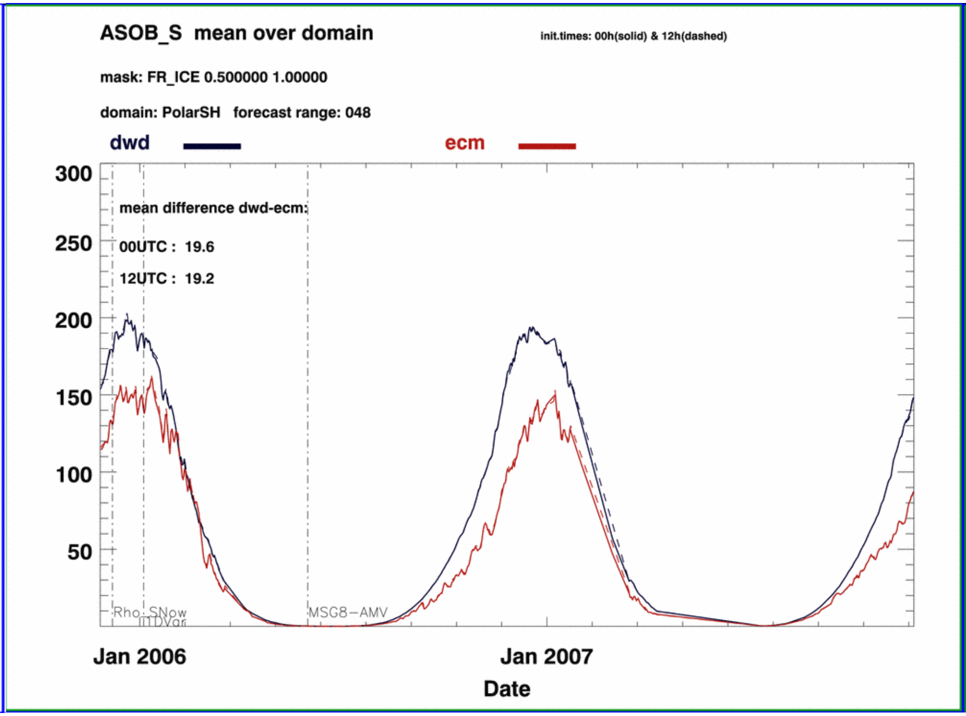
Net log-wave radiation flux at the surface from 48h forecasts of GME (**black**) and IFS ECMWF (**brown**). Left panel – Arctic, right panel – Antarctic.

In spite of lower θ_i and hence reduced upward long-wave radiation flux, the net surface energy loss due to long-wave radiation is higher in GME than in IFS.

Downward long-wave radiation flux is underestimated!

Performance of GME Sea Ice Scheme (cont'd)





Net solar radiation flux at the surface from 48h forecasts of GME (**black**) and IFS ECMWF (**brown**). Left panel – Arctic, right panel – Antarctic.

GME flux too high

Conclusions and Outlook

- ➔ Simple bulk sea ice and lake ice parameterisation schemes seem to be sufficient for NWP purposes
- ➔ Accurate prediction of low-level clouds and hence surface fluxes is a key issue
- ➔ Aggregation of fluxes over grid boxes partially covered by ice
- ➔ Ice/snow surface albedo
- ➔ Snow over sea and lake ice, an integral (bulk) snow model would be advantageous

Thank you for your attention!

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Appendix

Analogy to the Concept of Self-Similarity of the Temperature Profile in the Thermocline

Put forward by Kitaigorodskii and Miropolsky (1970) to describe the temperature structure of the oceanic seasonal thermocline. The essence of the concept is that the temperature profile in the thermocline can be fairly accurately parameterised through a "universal" function of dimensionless depth, using the temperature difference across the thermocline, $\Delta\theta=\theta_s(t)-\theta_b(t)$, and its thickness, Δh, as appropriate scales of temperature and depth:

$$\frac{\theta_s(t)-\theta(z,t)}{\Delta\theta(t)}=\vartheta(\varsigma),\quad \varsigma=\frac{z-h(t)}{\Delta h(t)}$$

Bulk Lake/Sea Model – Summary (cont'd)

Ice growth and/or melting from below

$$C_* h_i \frac{d\theta_i}{dt} = -\frac{1}{\rho_i c_i}\left(Q_a + I_a\right) - \Phi_i'(0)\frac{\kappa_i}{\rho_i c_i}\frac{\theta_i - \theta_f}{h_i}\left[1 + \left(1 - C_*\right)R\right],$$

$$\frac{dh_i}{dt} = -\Phi_i'(0)\frac{\kappa_i}{\rho_i L_f}\frac{\theta_i - \theta_f}{h_i}, \quad C_* = \int_0^1 \Phi(\varsigma)d\varsigma, \quad R = \frac{c_i\left(\theta_i - \theta_f\right)}{L_f}$$

Temperature profile shape factor

Ice melting from above

$$\theta_i = \theta_{f0}, \quad \left[1 + \left(1 - C_*\right)R\right]\frac{dh_i}{dt} = \frac{1}{\rho_i L_f}\left(Q_a + I_a\right)$$

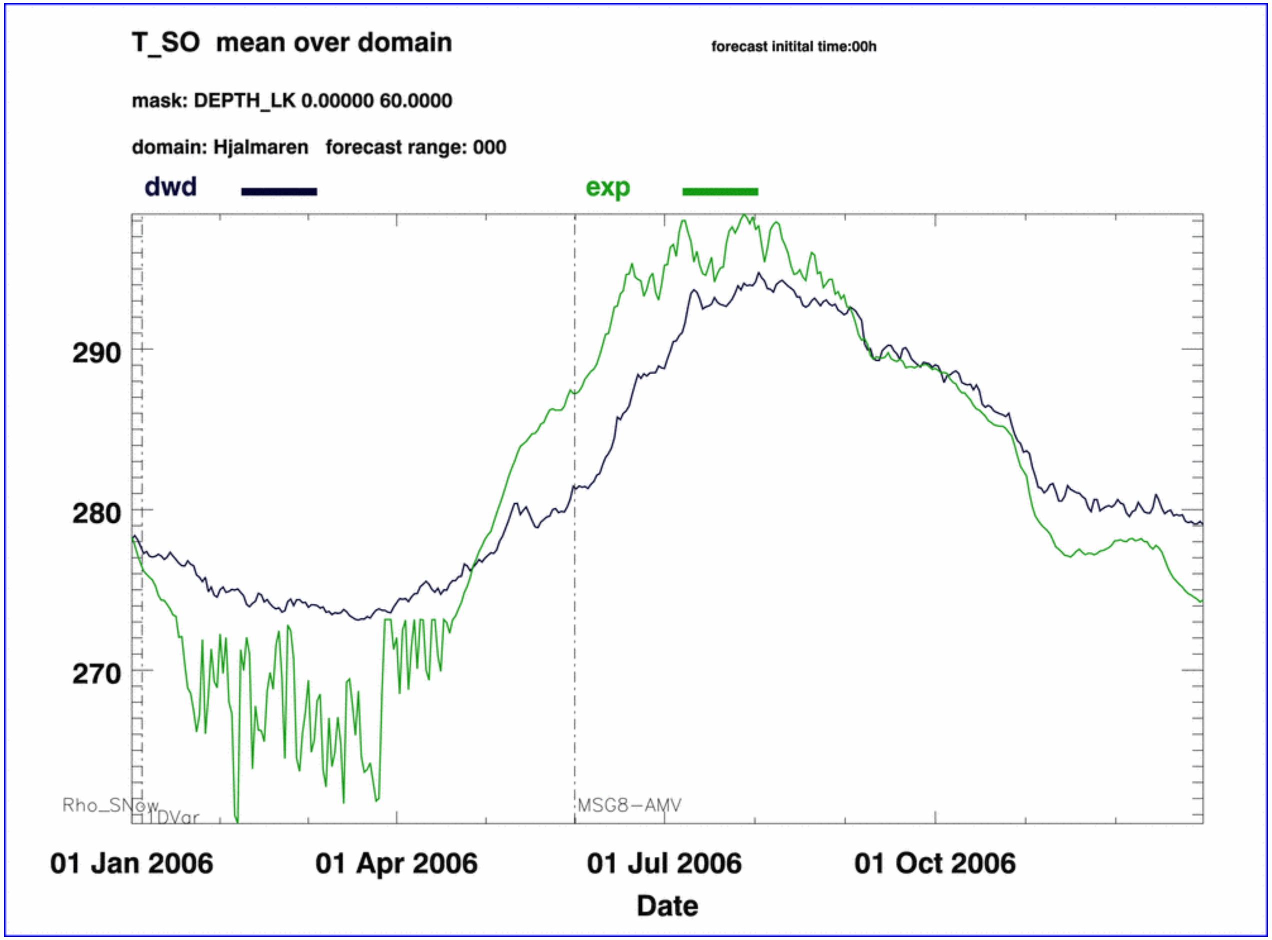
Bulk Lake/Sea Model – Summary (cont'd)

Snow over sea/lake ice is not treated explicitly. The effect of snow is accounted for implicitly (parametrically) through the changes in surface albedo with respect to solar radiation.

$$\alpha = \alpha_{max} - (\alpha_{max} - \alpha_{min}) \exp[-C_{\alpha} (\theta_{f0} - \theta_i)/\theta_{f0}]$$

$$C_{\alpha} = 95.6, \quad \alpha_{min} = 0.40, \quad \alpha_{max} = 0.65$$

FLake in COSMO: Results from Parallel Experiment 5632
1 January – 31 December 2006



Lake Hjälmaren, Sweden (mean depth = 6.1 m)

- Black – lake surface temperature from the COSMO SST analysis
- Green – lake surface temperature computed with FLake

FLake in COSMO: Results from Parallel Experiment 5632
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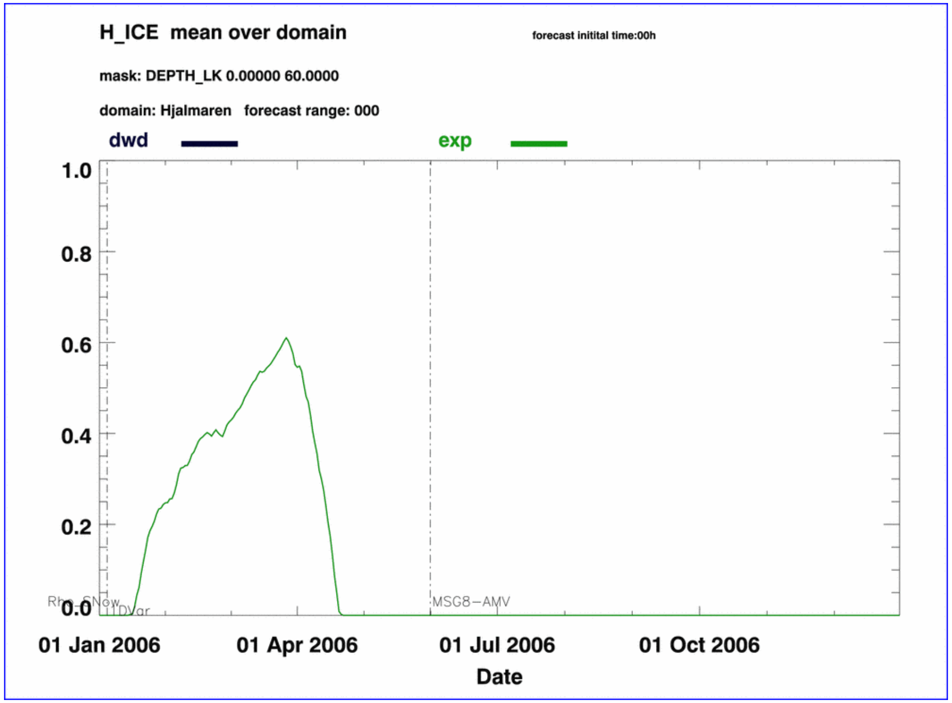
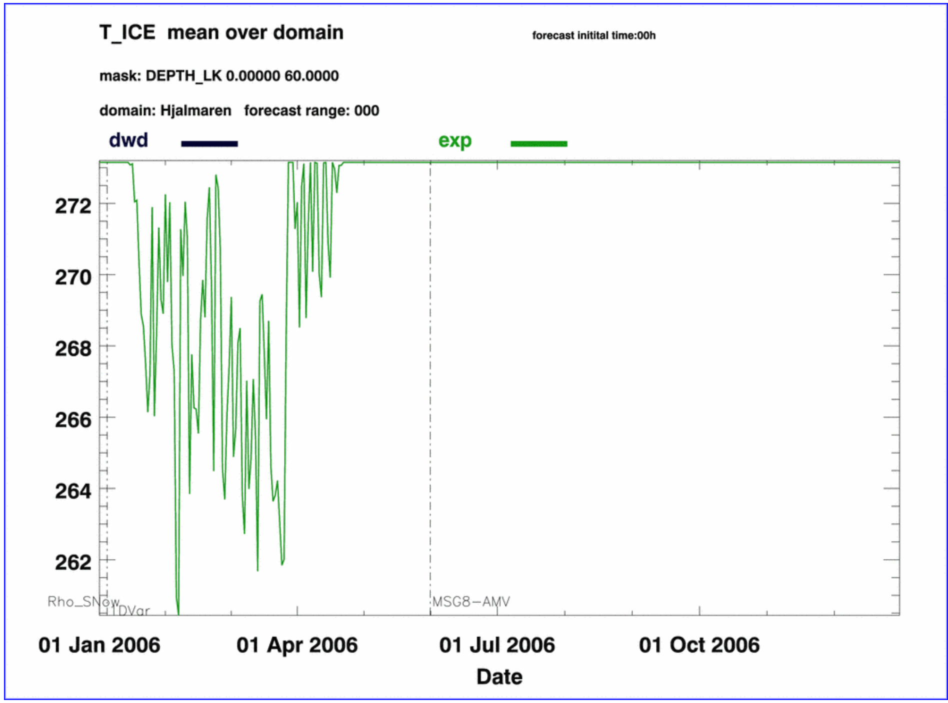


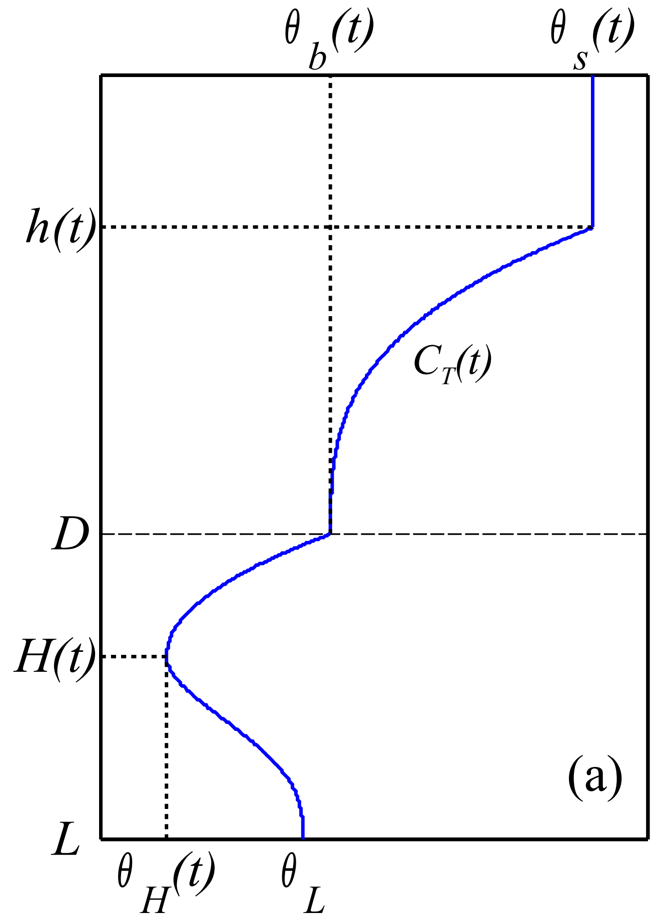


Lake Hjälmaren, Sweden (mean depth = 6.1 m)

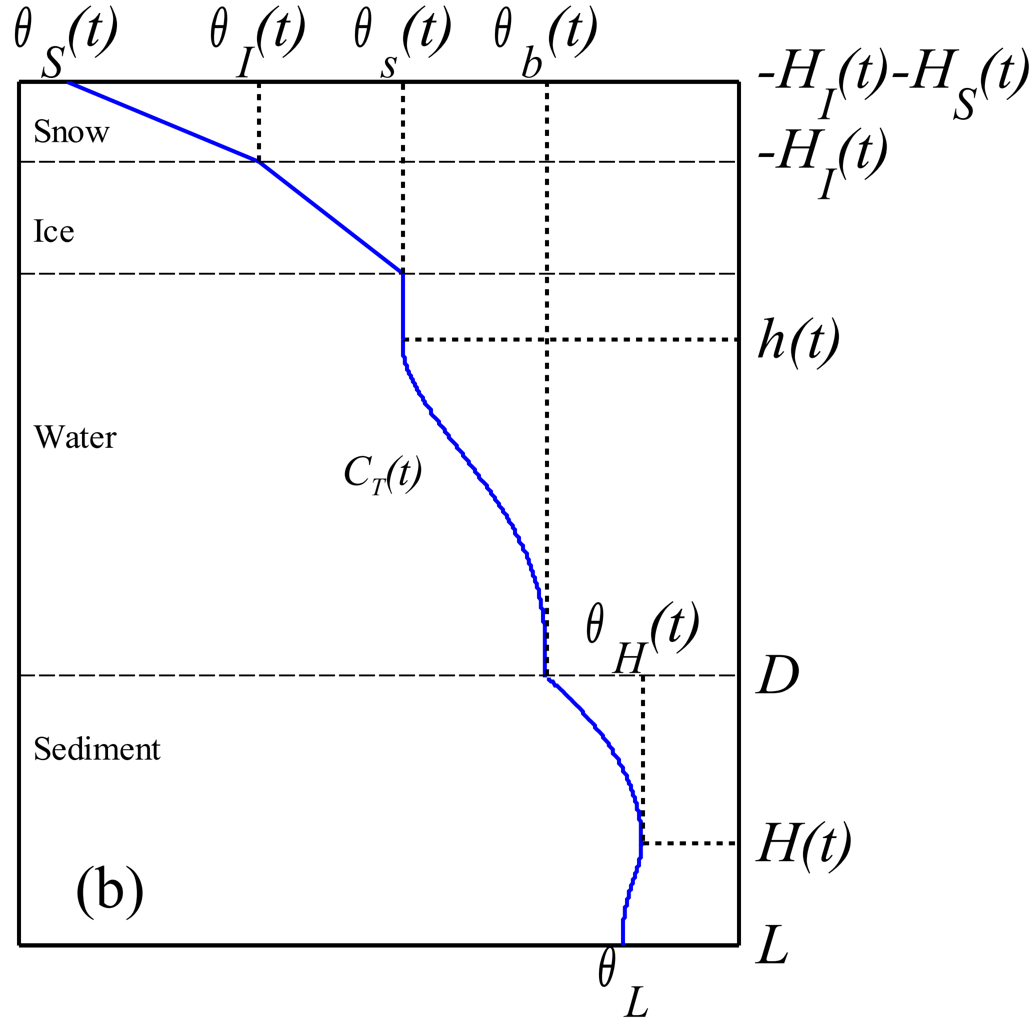
Ice thickness (left) and ice surface temperature (right)
computed with FLake

Unused

Schematic Representation of the Temperature Profile

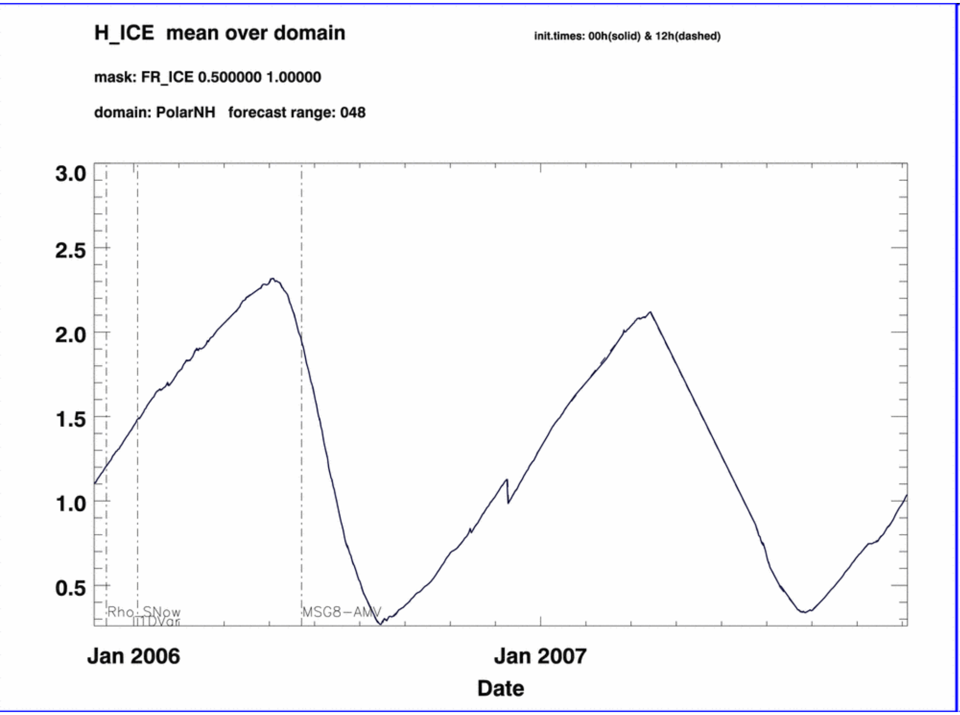


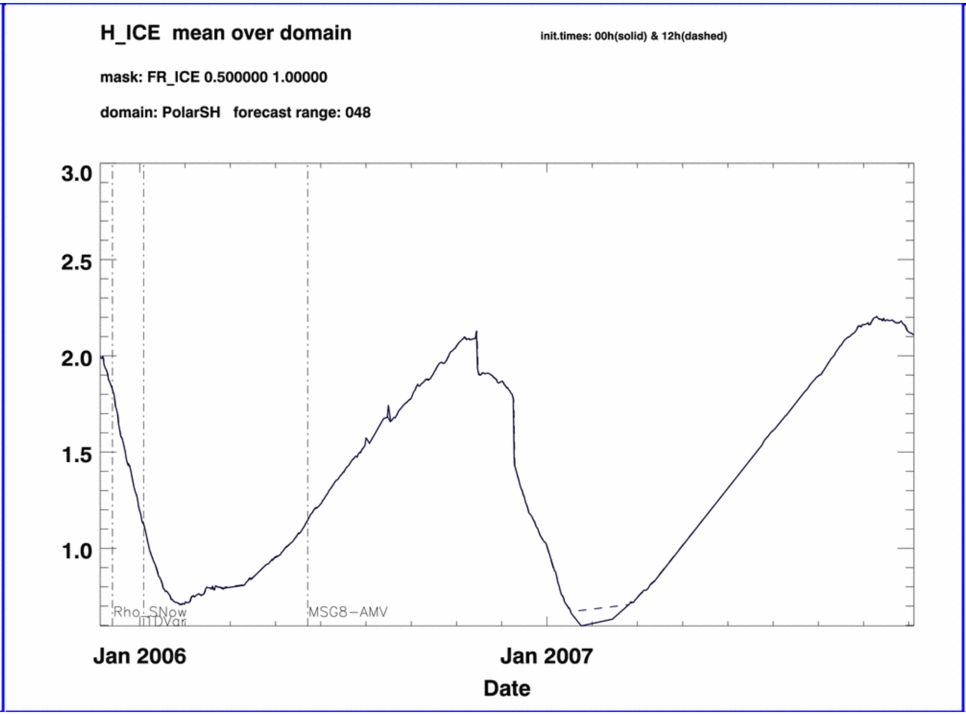
(a) The evolving temperature profile is characterised by a number of time-dependent parameters, namely, the temperature $\theta_s(t)$ and the depth $h(t)$ of the mixed layer, the bottom temperature $\theta_b(t)$, the shape factor $C_T(t)$ with respect to the temperature profile in the thermocline, the depth $H(t)$ within bottom sediments penetrated by the thermal wave, and the temperature $\theta_H(t)$ at that depth.



(b) For frozen lakes, four additional variables are computed, namely, the temperature $\theta_S(t)$ at the air-snow interface, the temperature $\theta_I(t)$ at the snow-ice interface, the snow thickness $H_S(t)$, and the ice thickness $H_I(t)$.

Performance of GME Sea Ice Scheme

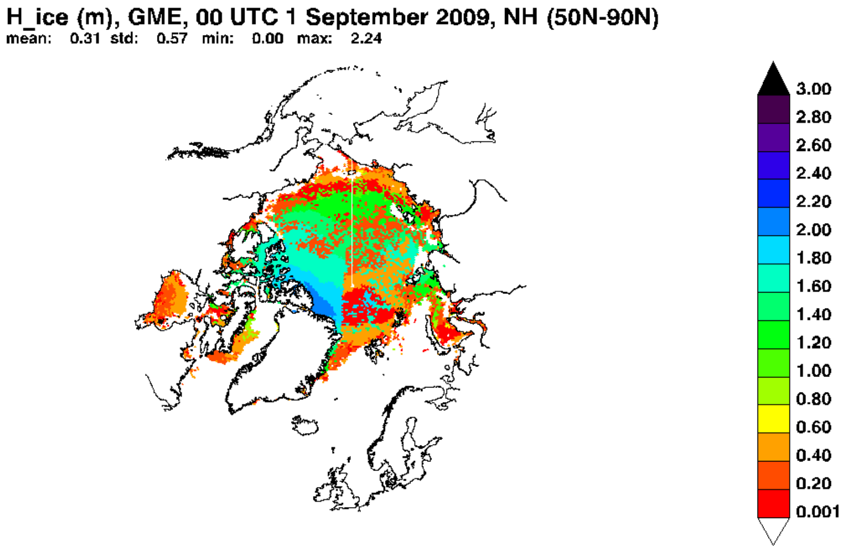


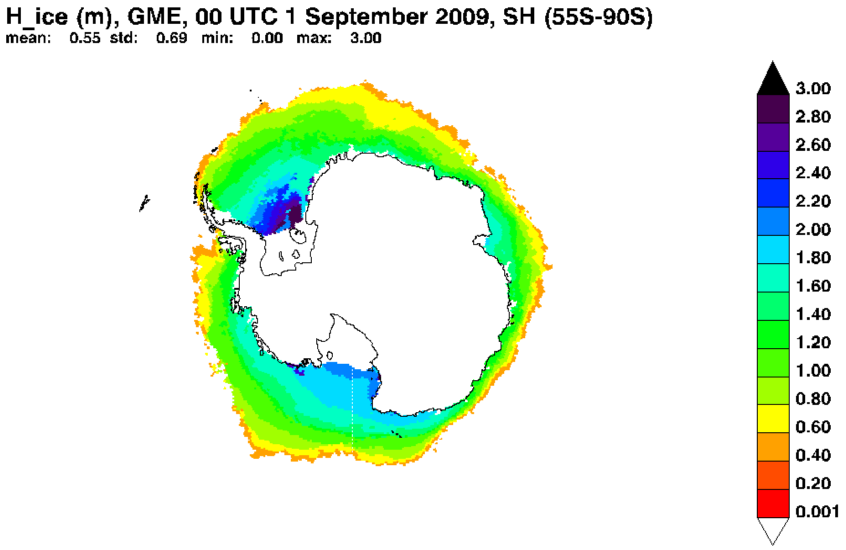


Ice thickness from 48h GME forecast.

Left panel – Arctic, right panel – Antarctic.

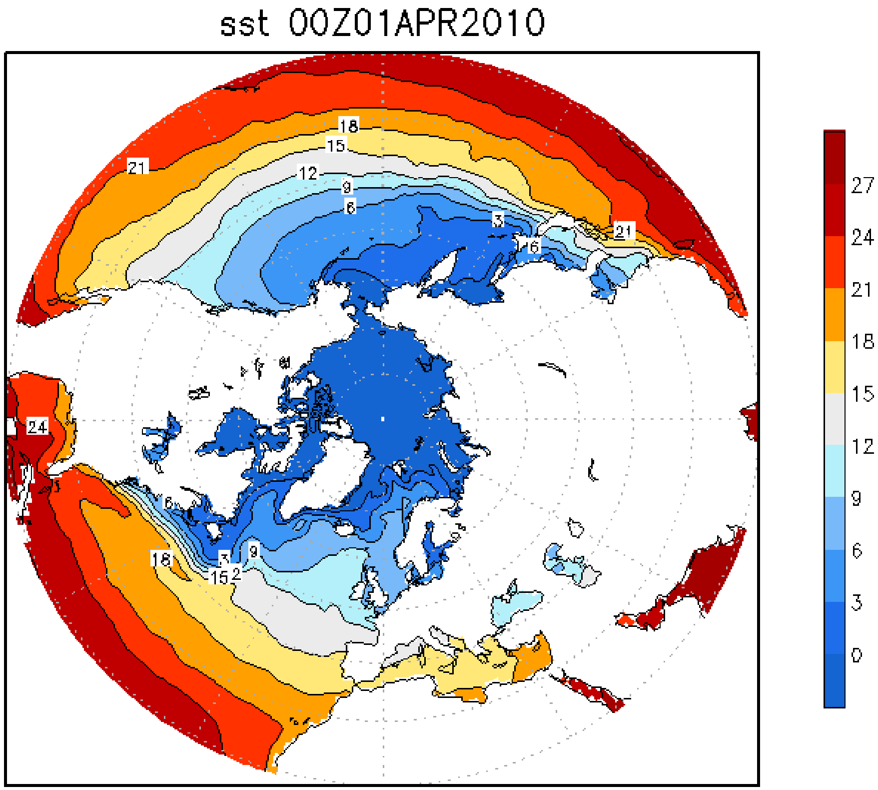
Performance of GME Sea Ice Scheme (cont'd)

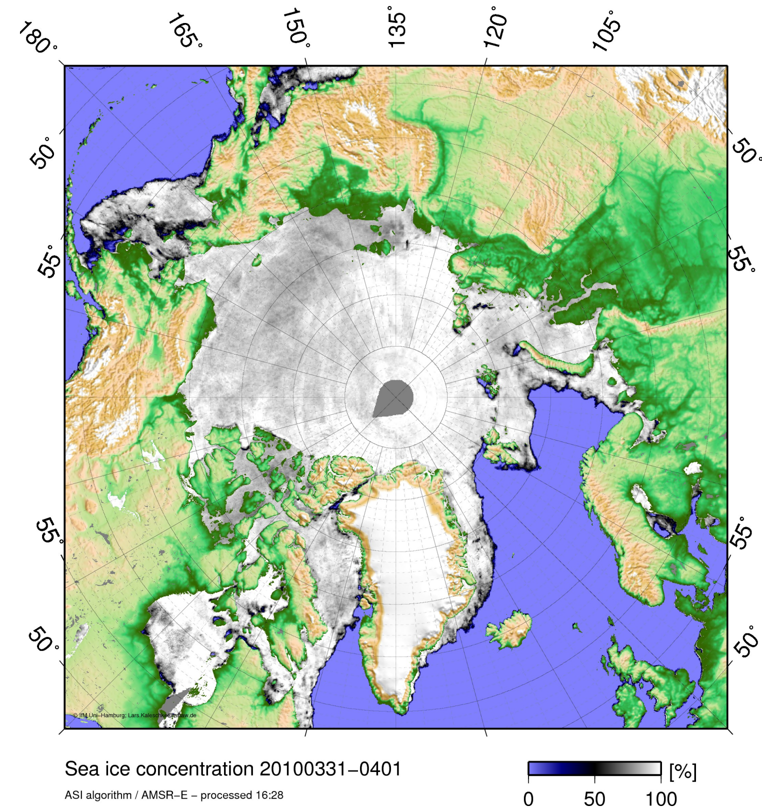




Ice thickness (m) from GME, 00 UTC 1 September 2009.
Left panel – Arctic, right panel – Antarctic.

Performance of GME Sea Ice Scheme (cont'd)

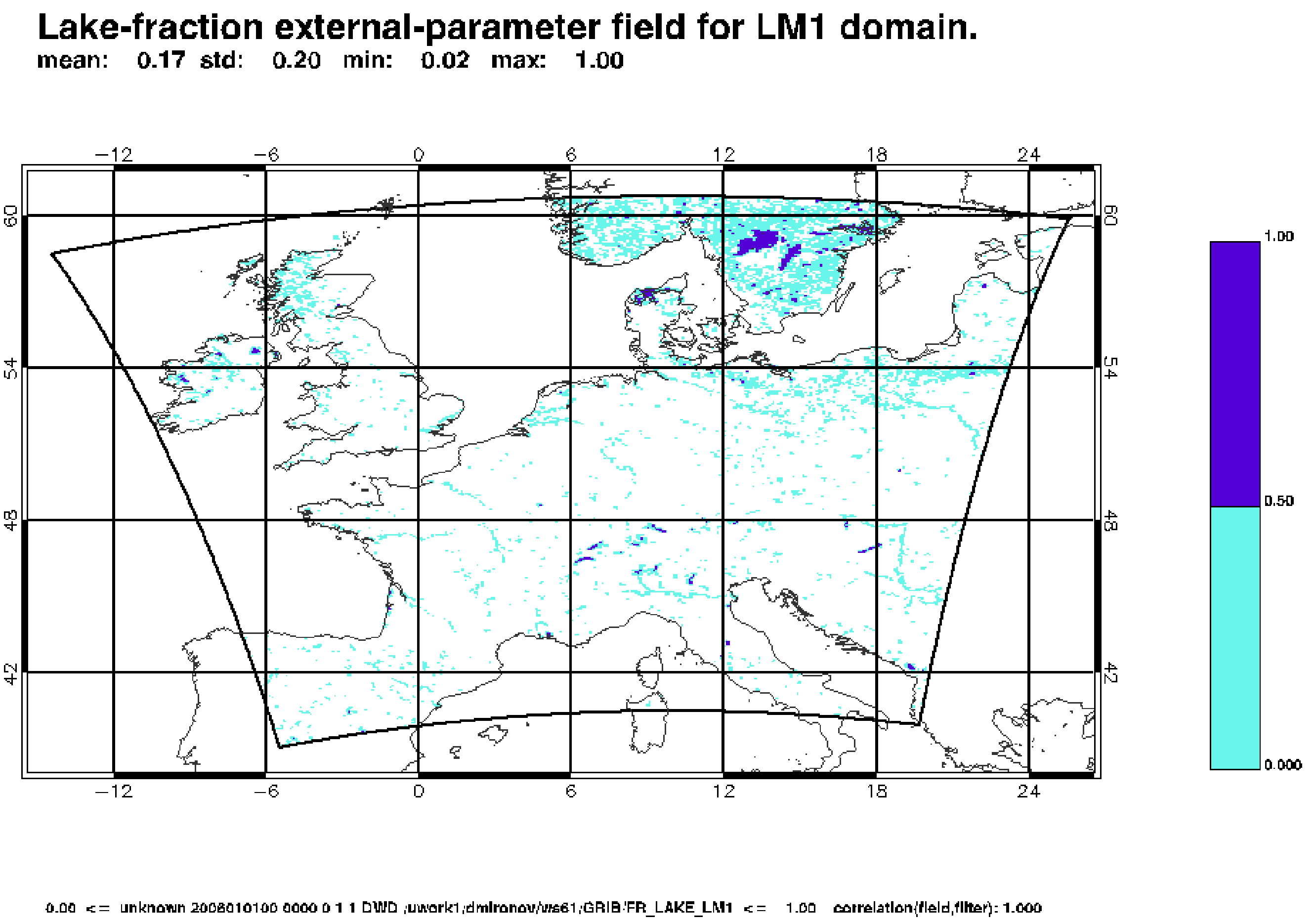




SST in the Arctic from observations, 1 April 2010.

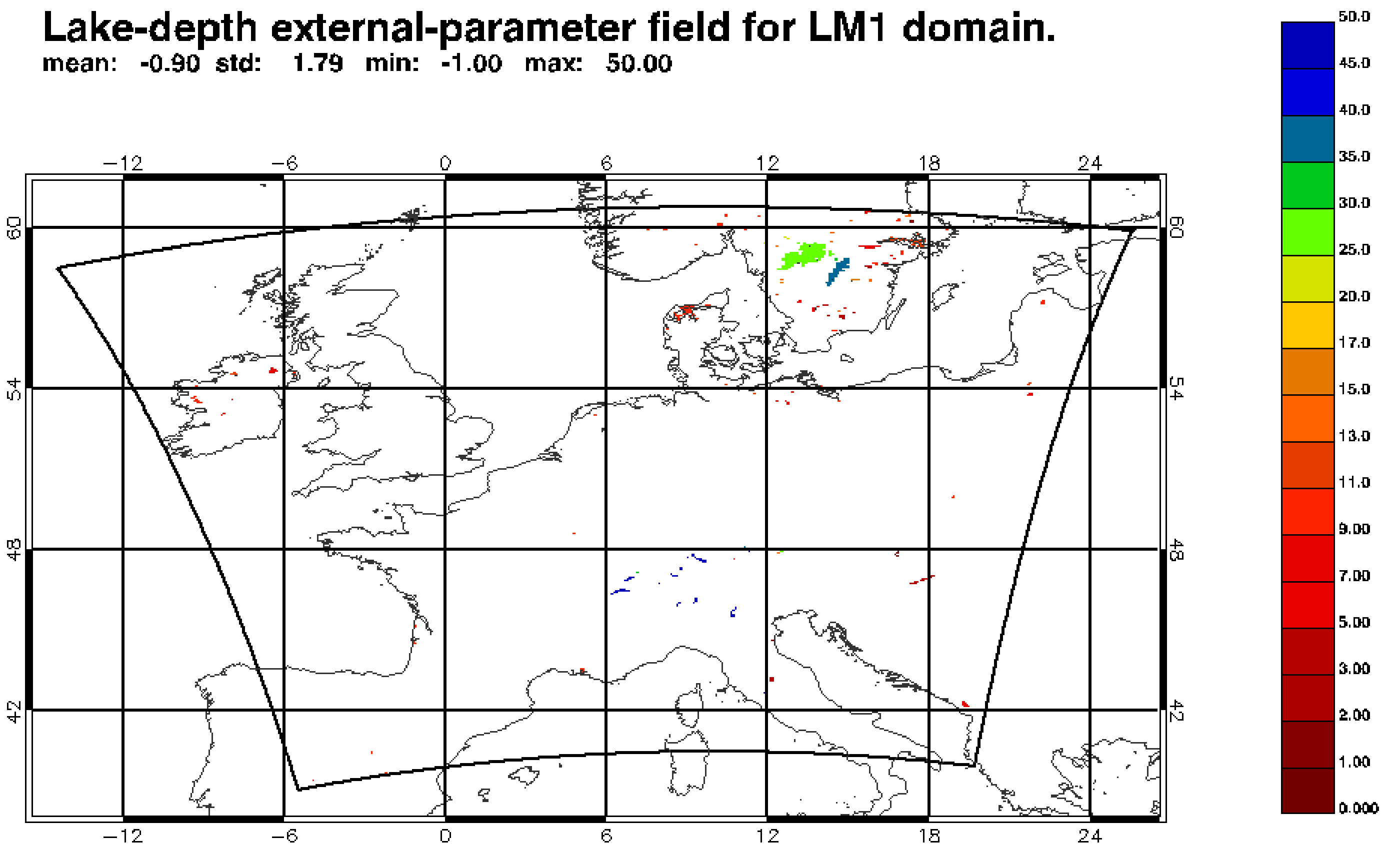
(Right panel: observed ice concentration.)

Lake Fraction



Lake-fraction external-parameter field for the LM1 numerical domain (DWD) of the NWP model COSMO based on the GLCC data set (http://edcsns17.cr.usgs.gov/glcc/) with 30 arc sec resolution, that is ca. 1 km at the equator.

Lake Depth



Lake depths for the LM1 numerical domain of the NWP model COSMO. The field is developed (Natalia Schneider) using various data sets. Each lake is characterised by its <u>mean depth</u>.

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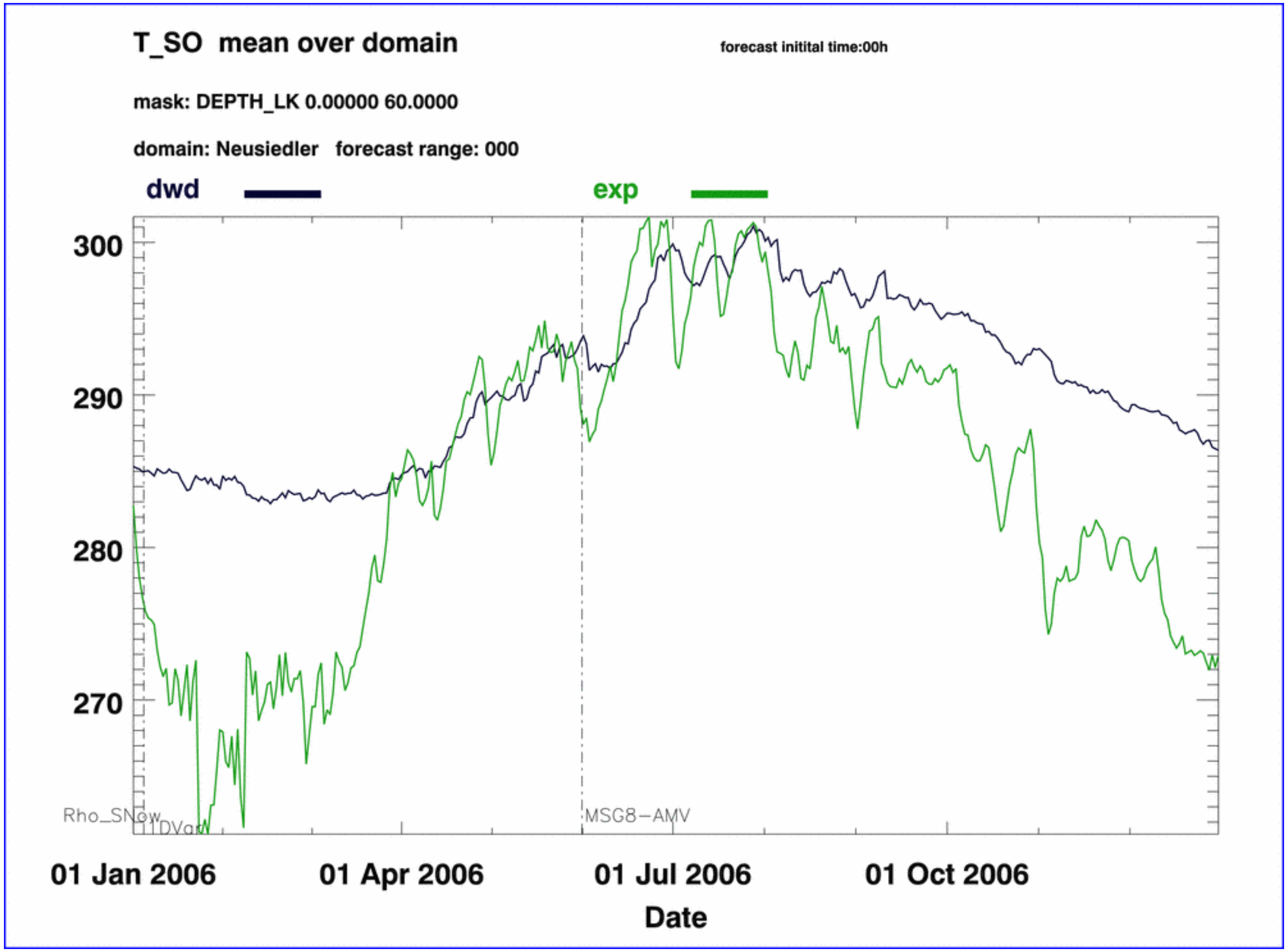

Neusiedlersee, Austria-Hungary (mean depth = 0.8 m)

- Black – lake surface temperature from the COSMO SST analysis
- Green – lake surface temperature computed with FLake