Integrating Activities for Advanced Communities

D4.3 Report on severe weather event case studies evaluation and implications for monitoring within INTERACT

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
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Publishable Executive Summary

Following the publication of D4.1 earlier this year, which reviewed the existing literature linking extreme events to biodiversity change and through discussions with other WP4 participants, it was decided to focus on forecasts of two types of extreme weather events: Arctic heatwaves and early and late snowmelt. The European Centre for Medium-Range Weather Forecasts (ECMWF) forecasts provided guidance of warmer than average temperatures up to 6-weeks in advance for both the 2018 European and 2020 Siberian heatwave. The potential role of land-atmosphere feedbacks in the predictability of these events is discussed. The forecasts of snowmelt revealed a severe bias in the snow depth and snow extent which becomes worse at longer lead times. Using data from the Sodankylä field site, this bias is attributed to a low bias in the incident solar radiation.

1. Introduction

The purpose of Task 4.3 was to evaluate the capability of the ECMWF-Integrated Forecasting System (IFS) to forewarn of the types of extreme events that can severely impact livelihoods and biodiversity within and around the Arctic region, and assess the availability of INTERACT data to inform forecasting system development. The approach taken was to select a number of extreme event case studies (of particular ecological and societal relevance) based on the outcomes of other tasks in WP4, and to conduct a process-oriented evaluation of these utilising, where possible, data collected at research stations that are part of the INTERACT network.

A literature review focussed on the ecological impact of extreme climatic events on Arctic terrestrial and freshwater biota was recently conducted for Task 4.1, with a view to informing future ecological monitoring activities in the Arctic. This study highlighted temperature extremes and related wildfires in the Arctic as being of particular interest. This combined with the large societal consequences associated with summer temperature extremes motivates focussing on this for the present report.

The following will present an investigation into two recent cases of extreme heat in the Arctic and one early and one late snow melt event. One of the heatwaves, the Siberian heatwave in 2020 resulted in the warmest temperature on record within the Arctic Circle. In this report, we will discuss the role of land-surface anomalies as drivers for the extreme temperatures seen during these events and associated biases. A short discussion on the availability and usability of data collected at relevant Research Stations within the INTERACT network will be made.

2. Arctic heat extremes

Heat extremes in the terrestrial Arctic have been increasing in recent decades (Dobricic et al., 2020), a trend which is expected to continue into the future (Landrum & Holland, 2020). Climate change attribution analysis of the 2020 Siberian heatwave found that conditions that human-induced climate change has dramatically increased the probability of occurrence and magnitude of extreme temperatures in the region and that the observed temperatures would have been almost impossible without human influence (Ciavarella et al., 2021). However, relatively few studies on forecast skill or the drivers of predictability for such events on timescales of a days-to-months exist.

Although they receive most attention it is not necessarily the highest temperatures in summer that are the only interest. Anomalously rapid or early snowmelt associated with warm spring temperatures can be disruptive and warm winter temperatures can have a negative impact on wildlife (de Flores, submitted). Such seasonal extreme events also provide an opportunity to study ecosystem responses in conditions analogous to what might be the norm in a future warmer climate. As such skilful predictions of anomalous temperature and snow cover could trigger responsive environmental monitoring activities in areas which are not continuously monitored.

3. Case studies

3.1. Case 1: Northern Europe 2018

The late spring and summer of 2018 were among the warmest on record for northern-western Europe. In Sodankylä, Finland, maximum daily temperatures were far above average for about a month around July-August with July 19th being the warmest (Fig 1). This was the warmest during the 111-year history of the station. Hot days in Finland tend to go hand in hand with high pressure anomalies, indicative of anticyclonic circulation (Kim et al., 2018), such as those seen in Fig 2.

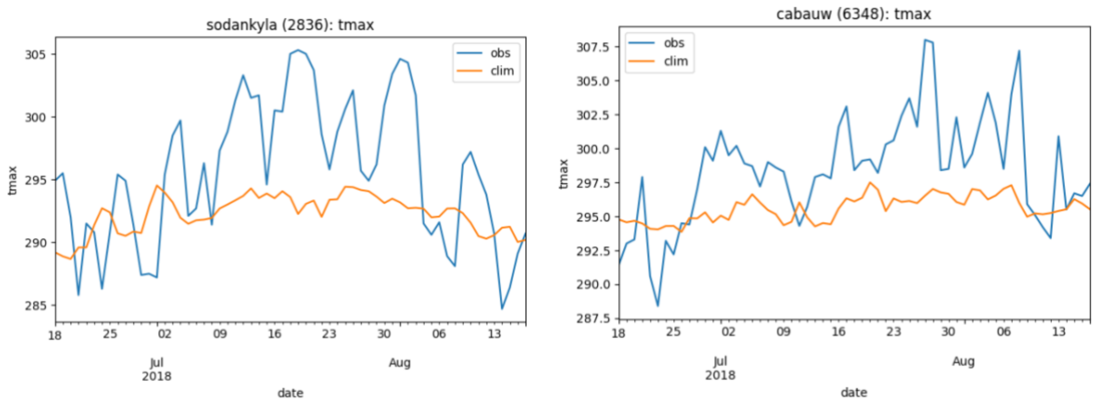

Fig 1. Observed timeseries of daily-maximum temperature at Sodankylä, Finland (left) and Cabauw, Netherlands (right), during Jun-Jul 2020 (blue). Climatology of daily-maximum temperature for the proceeding 20-years is shown in Orange. The location of Sodankylä and Cabauw are shown in Fig 2a, in green and purple respectively.

The heatwave also affected the UK and the Netherlands (Fig 1, right graph), with large temperatures corresponding with a ridge of high pressure that builds initially over the UK in late July and then extends and builds over northern Europe through until the end of August (Fig 2). The temperature anomaly goes hand-in-hand with reduced soil-water volume in the upper soil layer as warmer temperatures lead to enhanced evaporation from the surface.

The temperature anomaly over Europe was well forecast more than 4 weeks in advance, particularly over western Europe. Although at the longer lead times, the anomalies are largest over central Europe instead of in Scandinavia and Finland, as they were in reality.

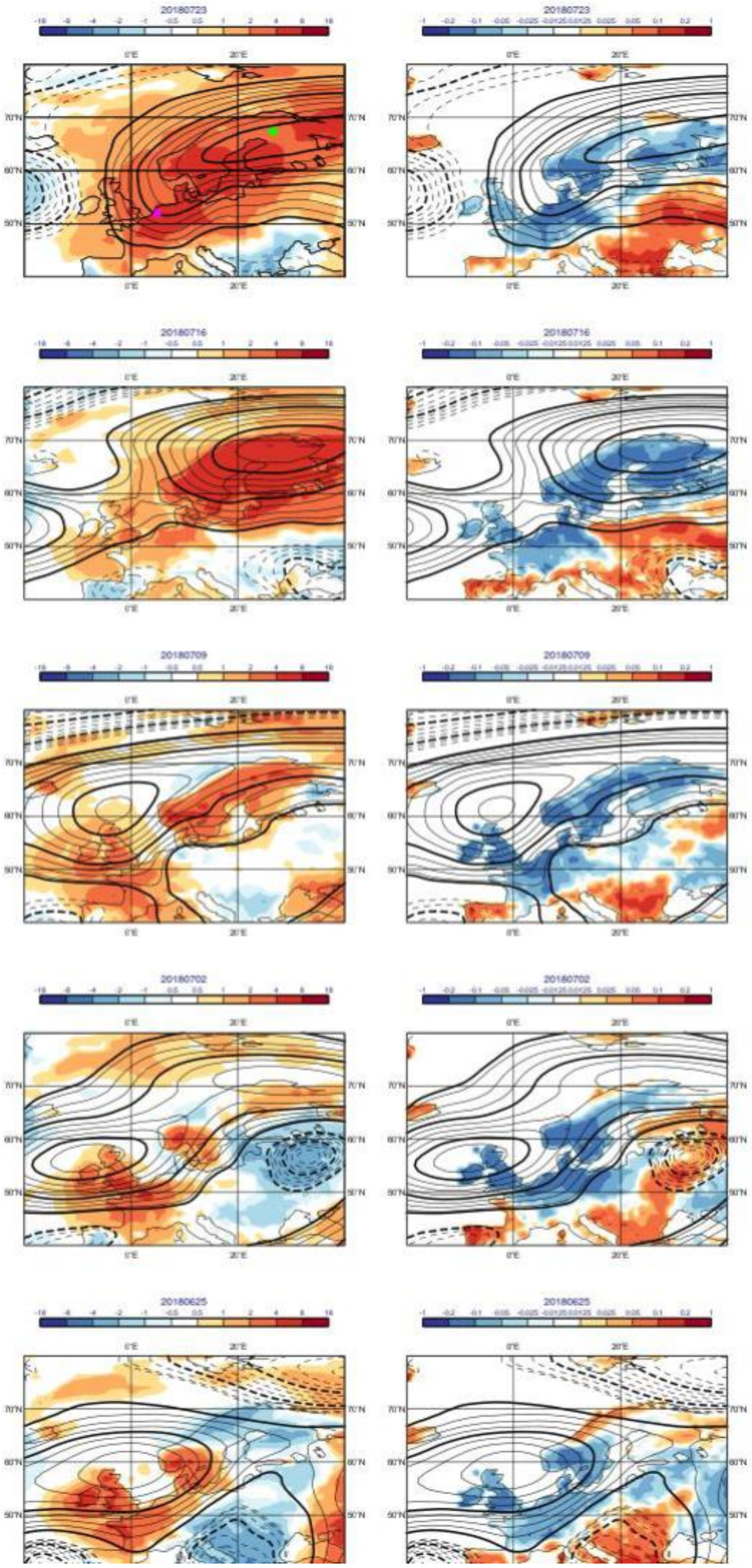

Fig 2. Weekly anomalies of 2m temperature (left), soil moisture at 7cm (right) from the ERA5 reanalysis for weeks starting 25-6-2018 through to that starting 23-07-2018. Anomalies of 300hPa geopotential height are overlayed with solid lines indicating anomalously high z and dashed lines indicating low z.

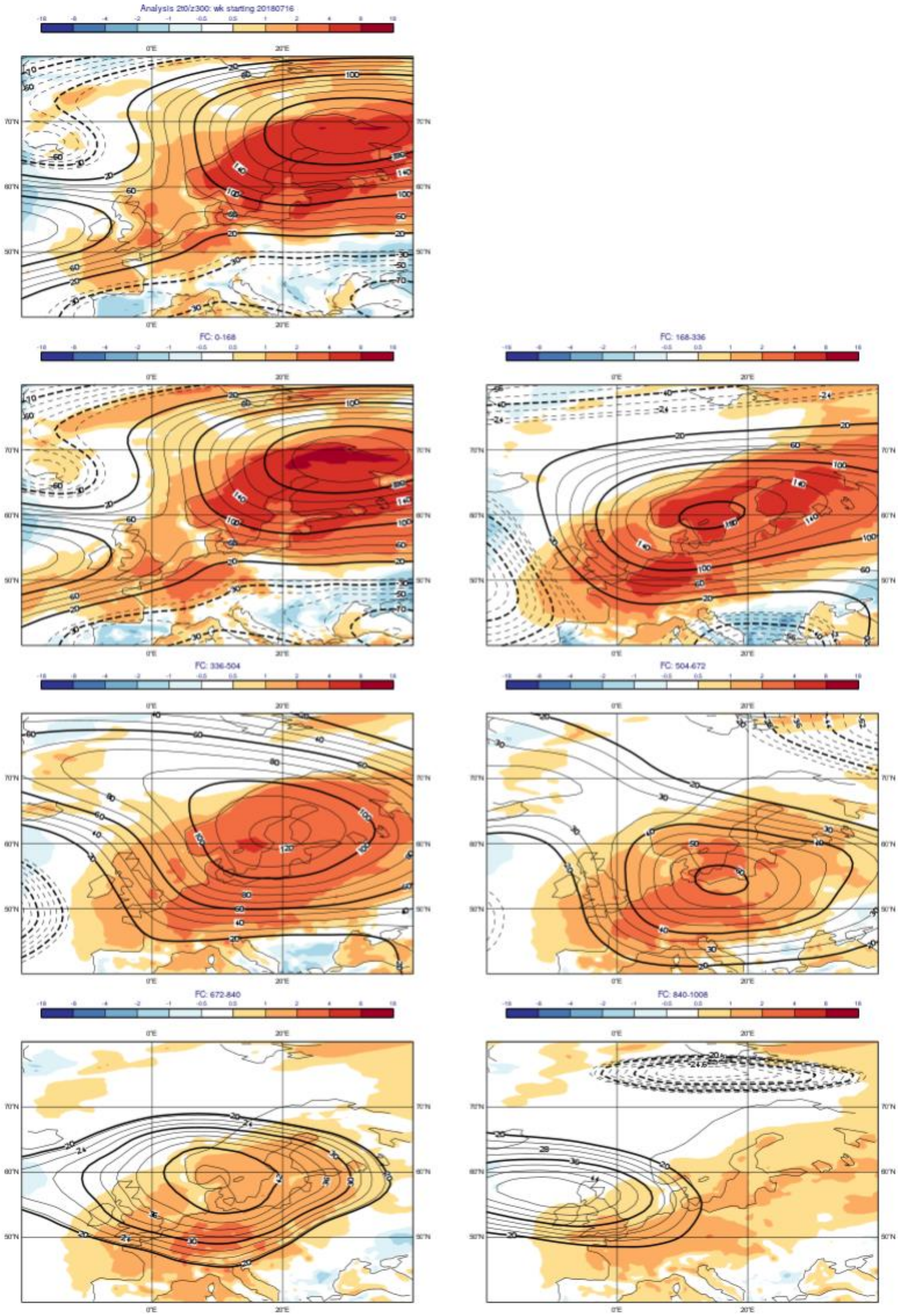

Fig 3. 2m-temperature and 300hPa geopotential anomaly for the week starting 16-7-2018 (top) and the weekly anomaly forecast for that week from 0, 1, 2, 3, 4 and 5 weeks in advance.

The high skill at long lead-times suggests a strong external forcing. One potential source of this is anomalies in land-surface conditions. Although early spring snowmelt and drier than average soil will have favoured warmer temperatures in early summer, soil moisture returns to average values before the heatwave itself, due to a rainfall event associated with an extratropical cyclone in late June, suggesting that the early spring snowmelt did not precondition the heatwave in the region above 60°N.

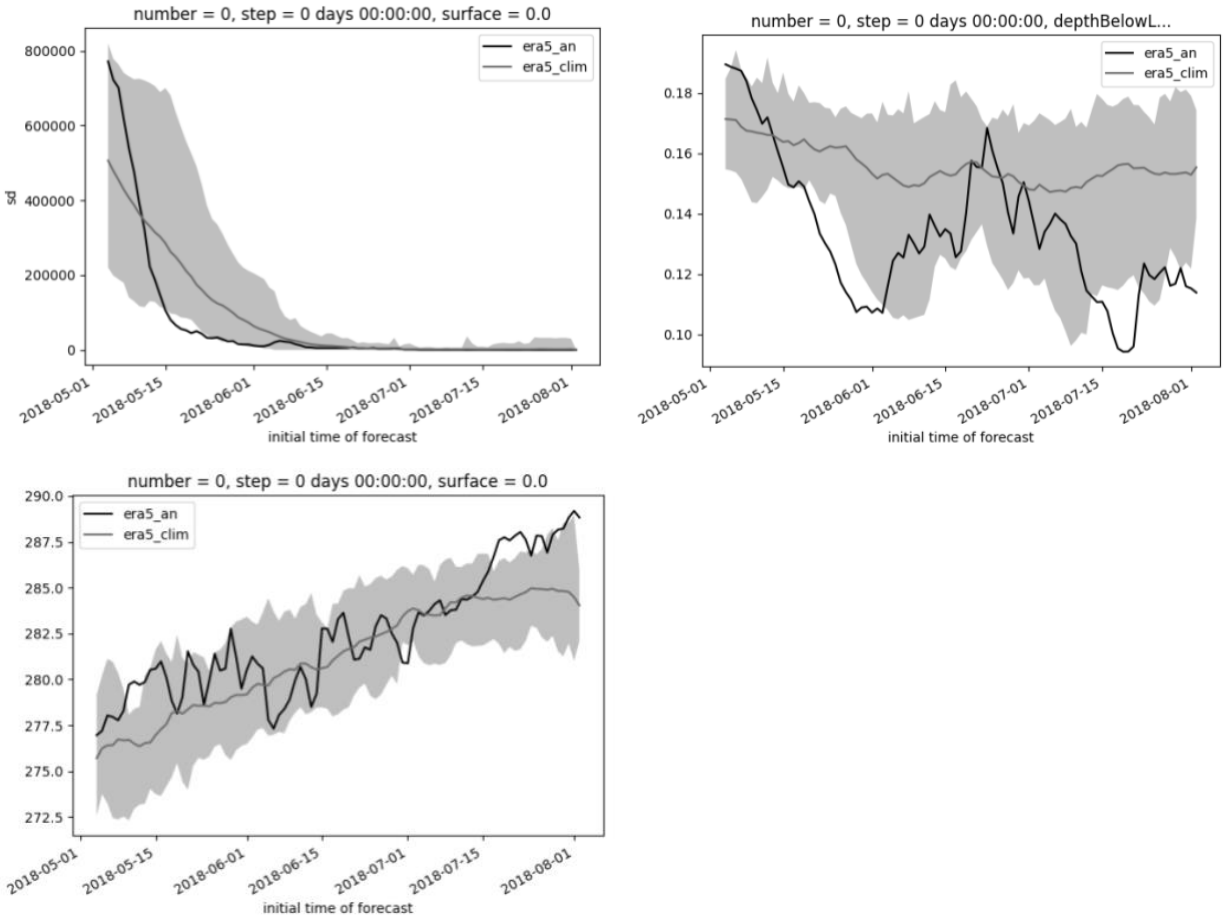

Fig 4. Timeseries snow extent, top left (in m²), 7cm soil moisture, top right (in m³/m³) and 2m temperature, bottom left (in K) from the ERA5 analysis for the box (60-73°N, 0-40°E) in black. The climatological mean is in dark grey and the light grey shows the climatological range between the maximum and minimum values over the last 20 years for the calendar day.

3.2. Case 2: Siberia 2020

The heatwave in Siberia in 2020 effectively had two parts. The first half was anomalously warm in Siberia, potentially as a result of a near record strength stratospheric polar vortex and related Arctic Oscillation between Jan-Apr, which tends to favour a temperature dipole across the Arctic with warm anomalies over Eurasia and Cold anomalies over north America (Overland & Wang, 2021). In the early second half of the year, quasi-stationary high wavenumber circulation patterns dominate through July 2020 resulting in the warmest Arctic temperature in the instrumental record being recorded at Verkhoyansk (Fig 5).

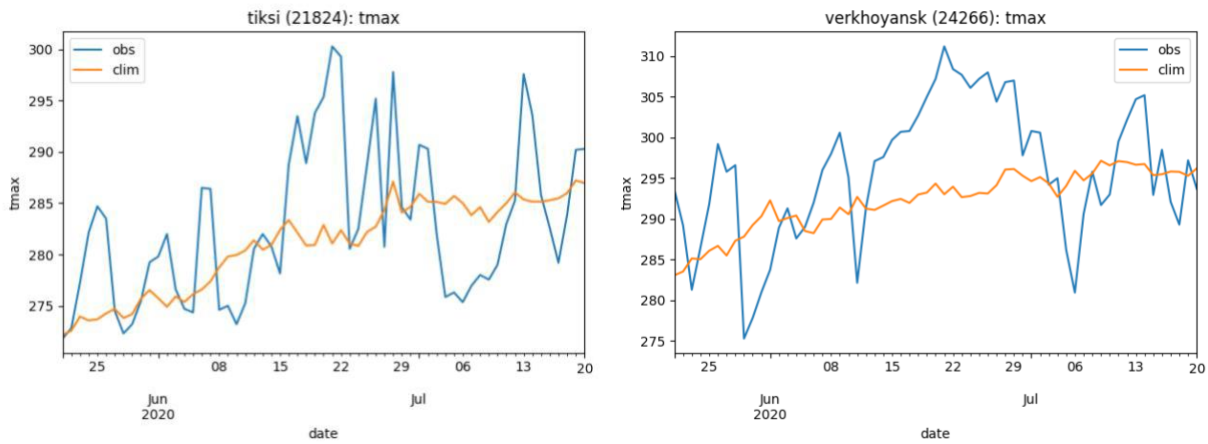

Fig 5. Observed timeseries of daily-maximum temperature at Tiksi and Verkhoyansk during Jun-Jul 2020 (blue). Climatology of daily-maximum temperature for the proceeding 20-years is shown in Orange.

From the first week in June there is a tripole in z300 across Eurasia, with high z300 anomalies over Northern Europe and Eastern Siberia and low anomalies in between associated with warm and cold anomalies respectively. The persistent regions of high pressure correspond with 2m-temperature anomalies and subsequent drying of the soil. However, land-surface conditions are already quite anomalous in late May, with anomalously low snow-cover and dry soil over a band between 60-70°N across the eastern half of Eurasia and anomalously low snow-cover along the Eurasian coastline. In June, precipitation associated with a low pressure system erodes the dry anomaly in central Eurasia, but dry soil conditions persist to the east.

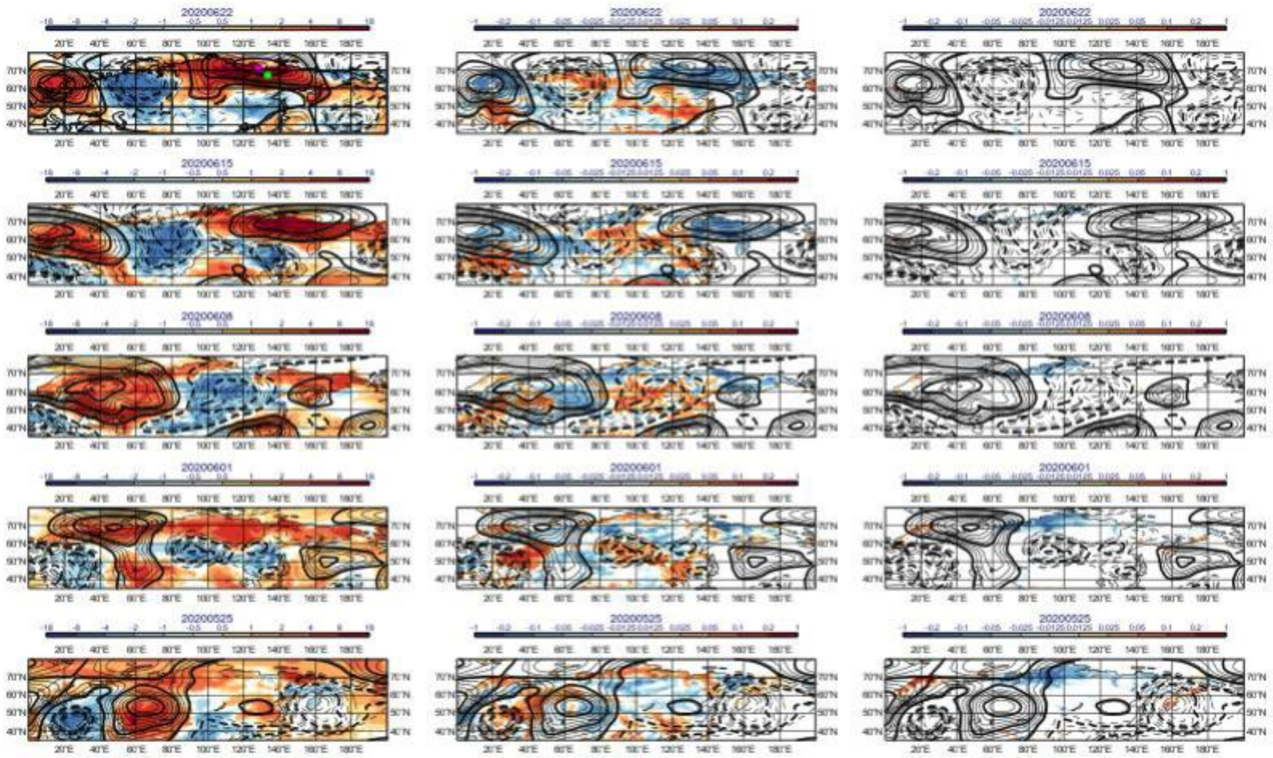

Fig 6. Weekly anomalies of 2m temperature (left), soil moisture at 7cm (middle) and snow depth (right) from the ERA5 reanalysis for week starting 25-05-2020 through to that starting 22-06-2022. Anomalies of 300hPa geopotential height are overlayed with solid lines indicating anomalously high z and dashed lines indicating low z.

The evolution of the forecast anomaly in Eastern Siberia was fairly consistent in the extended-range, with a warm anomaly forecast in the correct region of Siberia at all lead-times (Fig 7). The anomalies in z300 were captured from week 2 and at longer leadtimes a warm anomaly is correctly forecast. However, before two weeks ahead the z300 anomaly does not capture the observed high-wavenumber pattern. Instead a widespread positive anomaly in z300 is forecast across much of Eurasia.

The widespread pattern of anomalous z300 may be a response to anomalous snow and soil-moisture conditions which, numerical experimentation suggests, can force an upper level ridge (Ferranti & Viterbo, 2006).

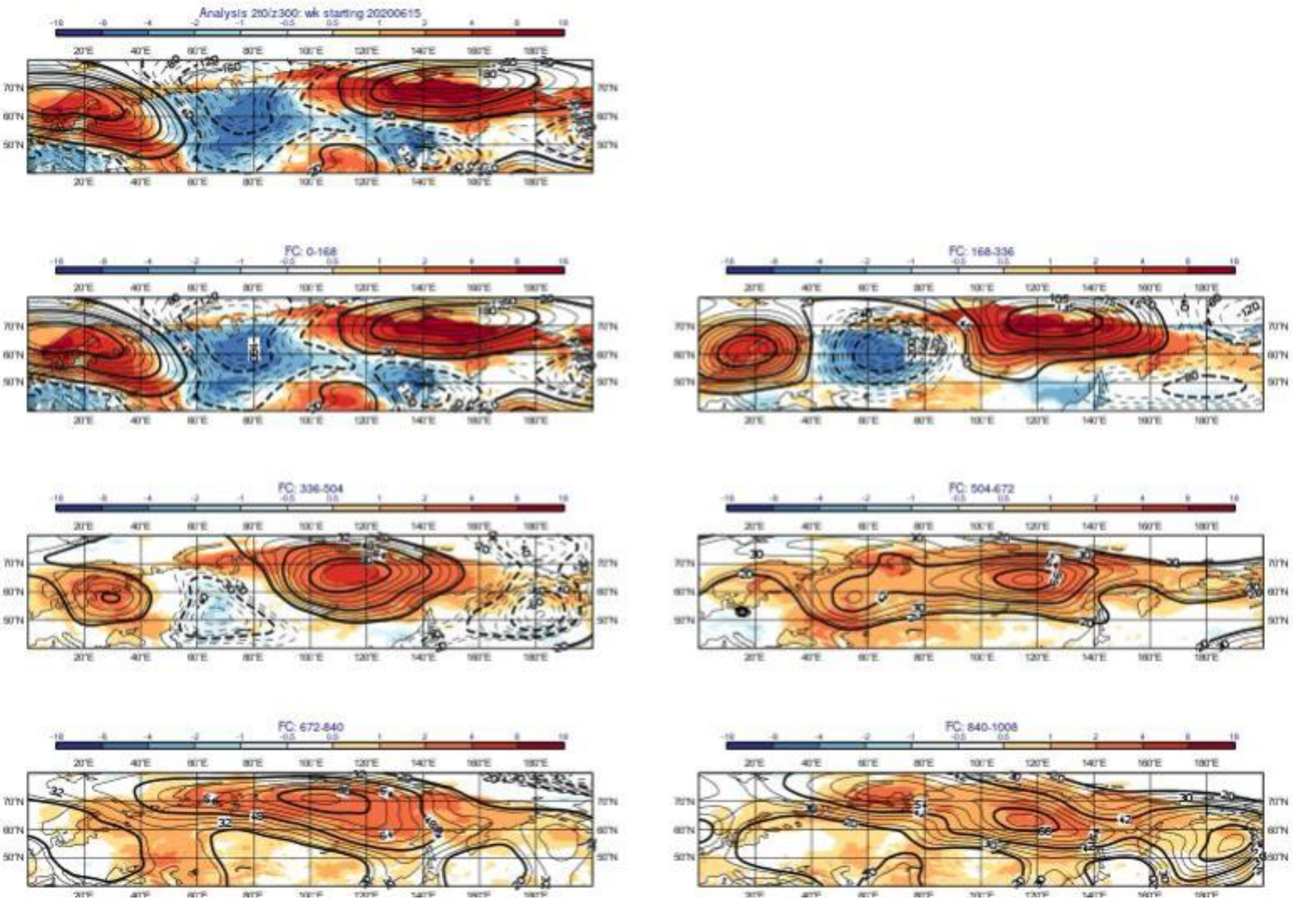

Fig 7. 2m-temperature and 300hPa geopotential anomaly for the week starting 15-6-2020 (top). And forecast anomaly for week 0, 1, 2, 3, 4, and 5.

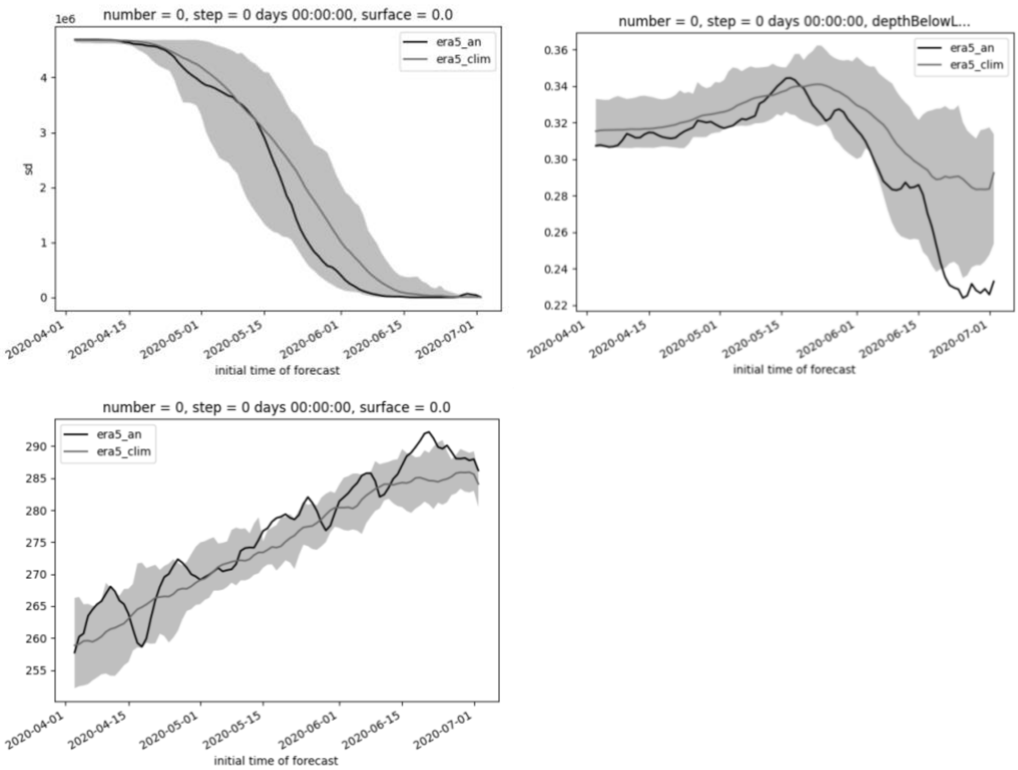

Fig 8. Timeseries snow extent, top left (in m^2), 7cm soil moisture, top right (in m^3/m^3) and 2m temperature, bottom left (in K) from the ERA5 analysis for the box (60-73°N, 100-180°E) in black. The climatological mean is in dark grey and the light grey shows the climatological range between the maximum and minimum values over the last 20 years for the calendar day.

4. Discussion on the role of land-surface aspects in extended-range predictability at high latitudes

The high predictability of the 2m temperature in the regions of extreme Arctic heat suggests a strong driver of predictability, such as that associated with Land-Atmosphere feedbacks.

Land-Atmosphere feedbacks play an important role in temperature extremes in some regions. Differences in land-surface properties, such as soil moisture can affect the rate at which the land-surface warms, with dryer soil heating up more rapidly than wetter ones. In regions where evaporation is moisture limited, the partitioning of sensible and latent heat is affected. Conversely warmer conditions lead to enhanced evaporation and drying of the soil creating a feedback loop. Soil moisture content can be a driver of extremes when water availability in the soil is a limiting factor for evapotranspiration (Santanello et al., 2018). It has been suggested that such conditions were prevalent during the 2018 Northern European heatwave, with soil moisture deficit amplifying the heatwave (Dirmeyer et al., 2021).

Soil moisture can also influence atmospheric circulation with drier initial conditions leading to a surface based low and upper level ridge (Ferranti & Viterbo, 2006).

In high latitudes spring snow cover anomalies provide another potentially important driver of temperature predictability. Snow cover acts as a fast climate-switch, with air-temperatures typically changing by 10K either side of the snow-onset and snow-free transition in seasonal snow zones (Betts et al., 2014). This temperature shift results from a dramatic increase in surface radiative heating due, in part, to reduced surface albedo when transitioning from snow to soil. Evidence for this can be seen from looking at timeseries of snow depth for various years from Sodankylä. For example, 2020 saw anomalously deep snow (~20cm larger than normal), which persisted through the spring and resulted in a late snow-free date (Fig 9).

A second mechanism through which snow depth anomalies can influence temperature predictability is via the soil moisture (Kolstad, 2017). Melting of the seasonal snowpack results in a large increase in soil moisture content prior to the snow-free date. In this mechanism, anomalously low snow depth tends to result in less moisture percolating into the soil, earlier snow-free date and an earlier timing of the annual soil moisture peak, leading to a deficit in soil moisture. This can then influence air temperature via the soil-moisture feedback mechanisms described above. Snow-temperature predictability mechanisms are most active in high latitudes around May-June time although the relative importance of each mechanism is not known (Kolstad, 2017).

A significant unknown is the importance of Land-Atmosphere feedbacks during heatwaves in permafrost zones. For example, whether permafrost is continuous or discontinuous can influence the hydrology, saturation and atmospheric conditions (Vecellio et al., 2019). Such distinctions are not made in the land-surface model coupled to the ECMWF-IFS.

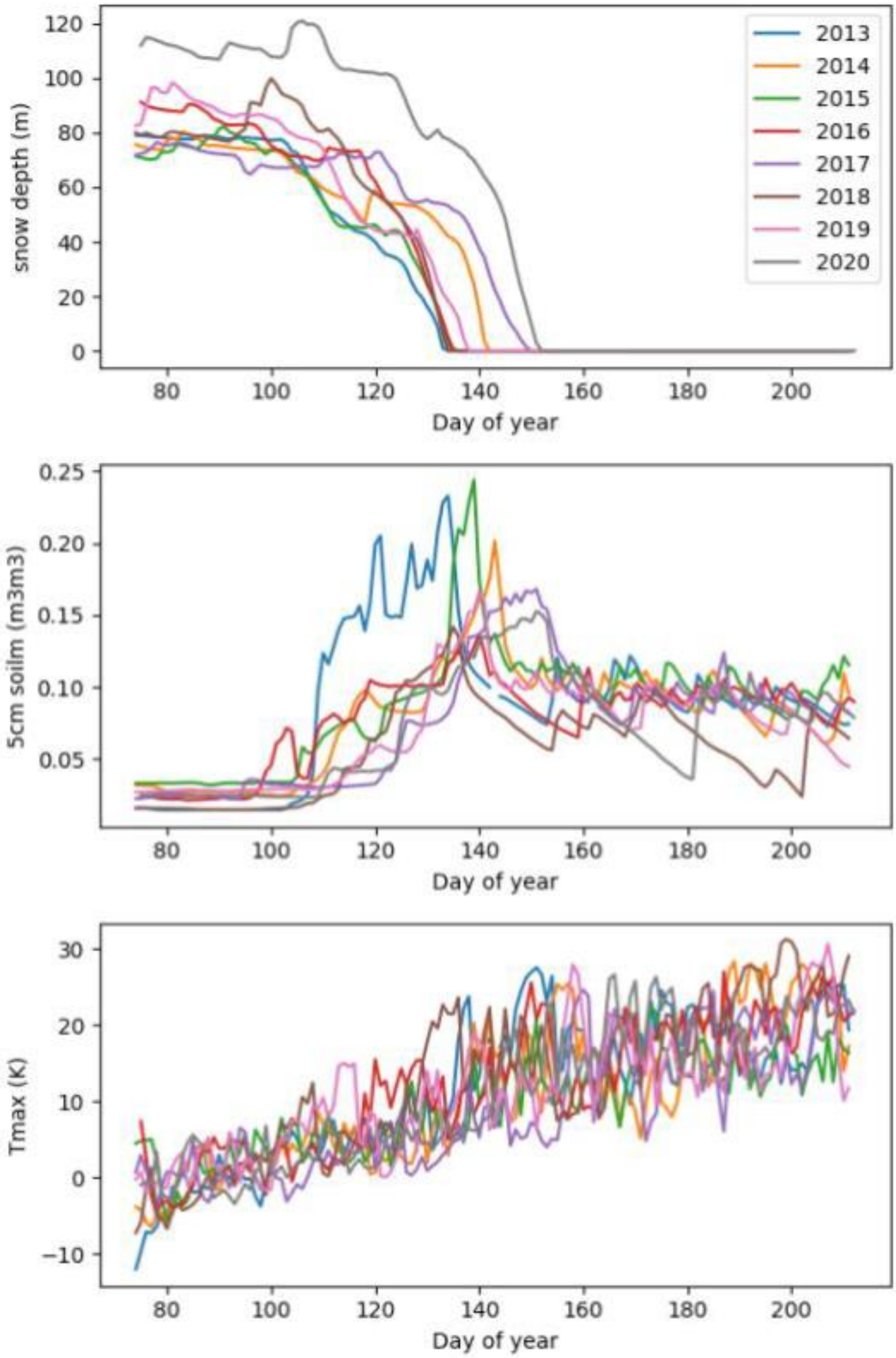

Fig 9. Daily timeseries of snow depth (top), 5m soil moisture (middle) and daily-maximum temperature (bottom) at Sodankylä. Timeseries for each year are plotted in a different colour.

5. Early and late snow-free dates in Sodankylä and the use of "supersite data" for forecast evaluation and improvement.

The global network of weather stations usually used to perform routine evaluation of weather forecasts only measure a limited number of variables (which typically include, 2m temp, 10m wind, relative humidity, cloud cover, ...). Data from meteorological observatories and research stations often includes a much richer suite of parameters, since they are often equipped with a tower measuring wind, humidity and temperature on several heights and also turbulent fluxes, radiation and land-surface cond. Typically data from such sites has not been used for routine evaluation of weather forecasts, due to the difficulty of interpreting the data, and due to a lack of standardisation and homogenisation of data collections from different observatories. However, such data offer the possibility to develop process-level understanding of the causes of systematic errors in weather forecasts, which may have multiple causes, that must be disentangled.

One such error is the slow snowmelt in the IFS, which can be clearly seen when comparing the model snow extent climate (turquoise line in Fig 10) with the observed (ERA5) snow extent climatology (grey line). After the initial time the model climate melts too slowly resulting around triple the snow cover observed after 6-weeks. This makes it hard to interpret the snow cover forecasts themselves, but will also affect the ability of the forecasts to correctly capture predictable variations in soil-moisture and surface exchange processes thereby resulting in temperature and circulation errors.

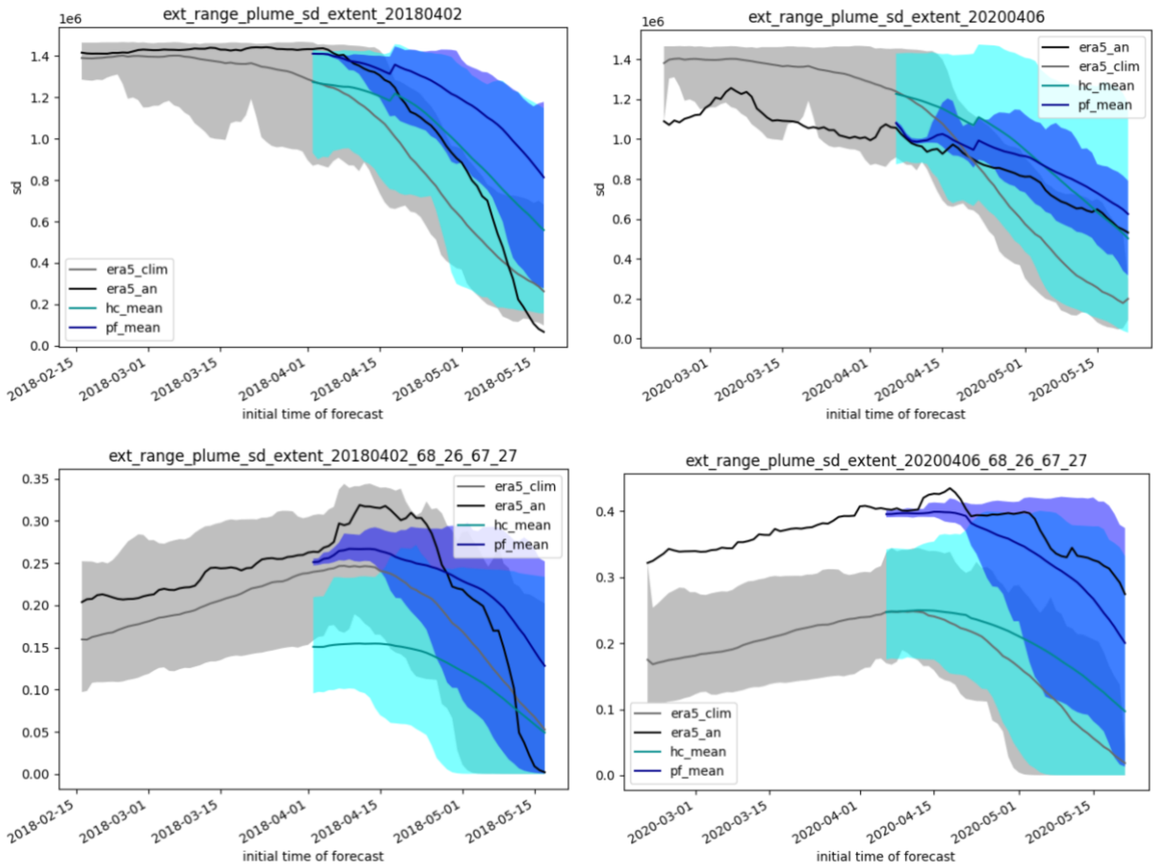

Fig 10. Timeseries of snow extent for Northern Europe (0-40°E, 60-70°N; top row) and snow water equivalent (SWE) (for Sodankylä; bottom row) from the ERA5 analysis (in black) for spring 2020 (right) and spring 2018 (left). The ERA5 mean snow extent and min-max range for the previous 20 years is shown in grey. The ensemble mean and min-max range in the extended-range forecast, initialised 6-4-2020 (right) and 2-4-2018 (left) is shown in blue and the mean and min-max for the hindcasts (initialised on the same calendar day for the previous 20-years) is shown in turquoise. Note that the hindcasts for the 2018 are initialised from the older ERA-Interim reanalysis, rather than ERA5, causing the mismatch in SWE in panel lower bottom left.

A number of INTERACT stations monitor snow depth and related meteorological parameters. Focussing at Sodankylä, which is the main high latitude snow-focussed observatory in Northern Europe one can ask if the conditions seen at this station are representative of the widespread pattern. To do this a set of 3-day forecasts initialised between 1 April and 15th May for the nearest model grid point to Sodankylä are compared with observations (Fig 11).

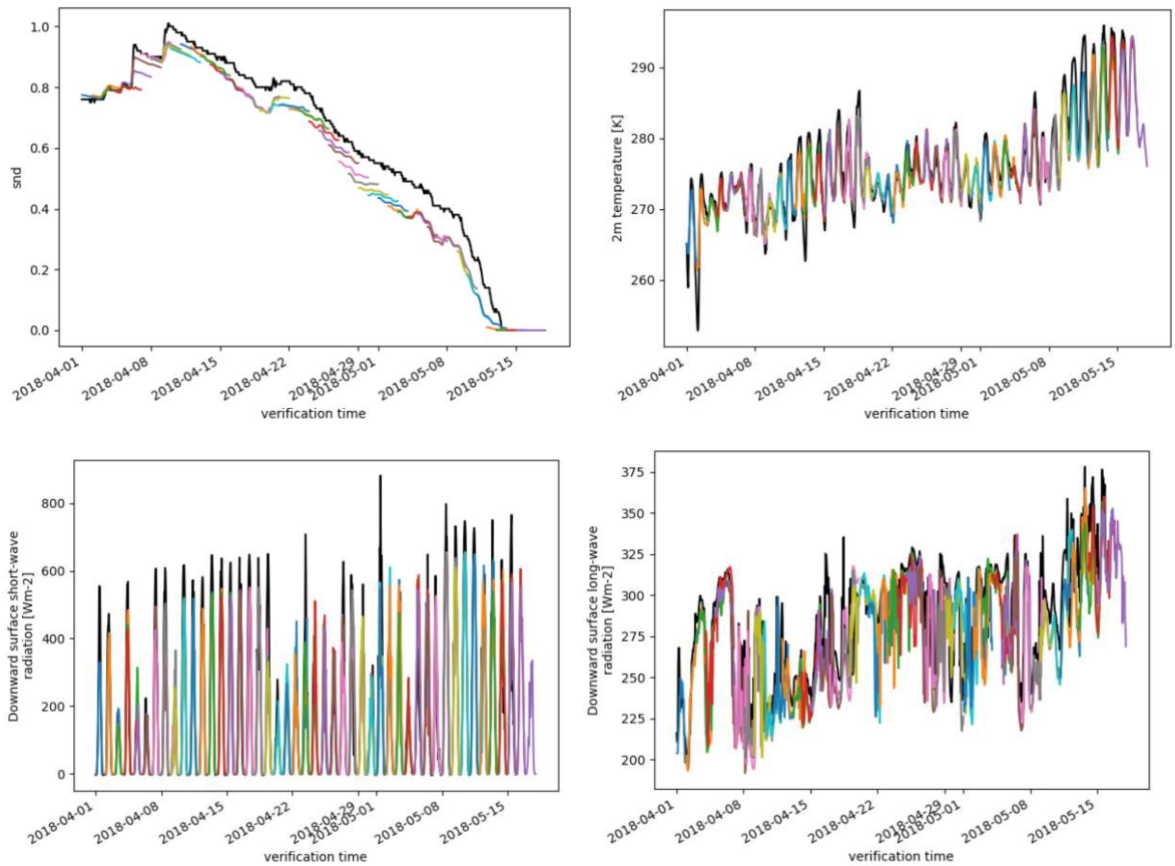

Fig 11. Timeseries of observed (black) and forecast (coloured) downwelling longwave radiation (top left), downwelling shortwave radiation (top right), snow depth (bottom left) and 2m-air temperature (bottom right). Each colour corresponds to a different 0UTC forecast, initialised between 1 April and 15th May.

Simply plotting timeseries of the observations and forecasts together reveals some interesting features (Fig 10). For example, an underestimation of the diurnal cycle of 2m-temperature (Fig 10 upper right) and an underestimation of the mid-day maximum of incoming shortwave radiation. However, it is harder to discern by eye whether the snow-depth is reducing too slowly or not.

During this time of year increases in insolation lead to melting of the snow and the rate at which this occurs relates to numerous processes relating to the amount of incident radiation, the density and albedo of the snow and the partitioning of the incident radiation to sensible, latent heat and the amount of absorption by the snow.

In the absence of snow accumulation, changes in snow depth are largely driven by radiation. This can be seen clearly by the strong relationship between the 3-day accumulated driving radiation at the surface, LW↓+SWnet, where LW↓ is the downwelling longwave radiation and SWnet is the net shortwave radiation and the 3-day change in snow depth (Fig 11 top left). As a result, one might expect an error in the rate of snow-depth change, such as seen in Fig 10, to either be the result of errors in the radiation, the response of the snow cover to that radiation or more likely a combination of both.

Plotting these terms, one can see that the sluggish snowmelt is evident after 3-days of the forecast, with the 3-day reduction in snow depth 10cm less in the forecasts than observations (Fig 12a). However, the sensitivity of snow-depth change to accumulated radiation has a larger magnitude in the forecasts compared to the observations, -5.3x10-9 m/J compared to -3.6x10-9 m/J. So if anything snow-melt is too sensitive to radiative forcing in the forecasts. The presence of a clear systematic low bias in LW↓+SWnet therefore suggests this is likely to be the main cause of the positive snow depth and snow extent bias in Northern Europe. However, the reasons for the bias in the incoming radiation and how geographically widespread this is, need to be investigated further.

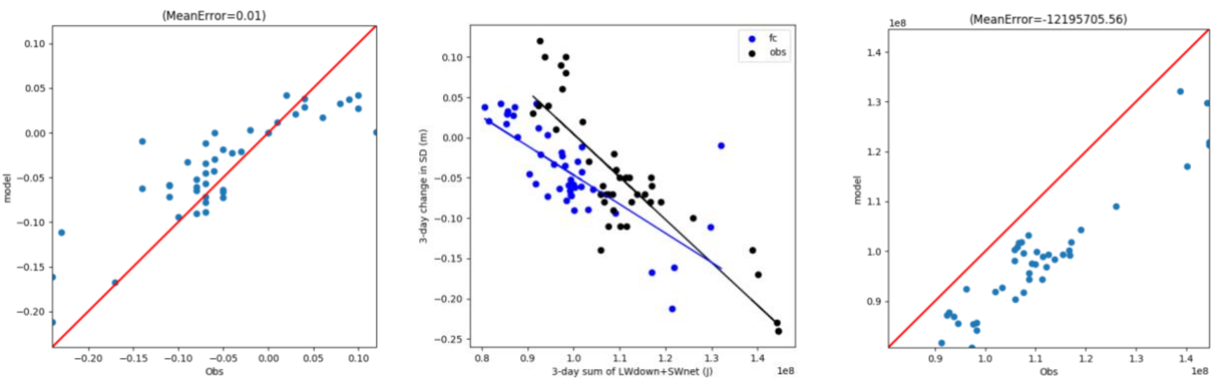

Fig 12. Scatter plot showing the relationship between the 3-day change in snow depth (in m) and the 3-day accumulated LW↓+SWnet (J) in observations (black) and forecasts (blue). The line of best fit is shown.

6. Conclusions

We have investigated the ability of ECMWF forecasts to forecast two recent extreme heat events in the Arctic and one late and one early snow melt event in Northern Europe. We have also provided an example of how the detailed observations collected at Sodankylä, one of the INTERACT research stations, can be used to improve understanding of the causes of poor snow cover forecast performance from a process-oriented perspective.

The main findings were:

- Positive temperature anomalies are forecast at least 6-weeks in advance for two recent high-latitude heatwaves considered.
- Based on timeseries analysis of the two cases and a review of the literature on land-atmosphere feedbacks for the two events we argue that land-surface processes played a role in amplifying the two heatwaves.
- Forecasts of North European snow cover show a severe snow depth bias, with the model climate producing much larger values than the observations at longer lead times.
- Process-oriented analysis of a set of 3-day forecasts suggests that a bias in the incident shortwave radiation is likely to be an important cause of this snow depth bias in spring.

7. Next Steps

There are many outstanding challenges with the use of observatory data, which includes variables originating from scores of instruments, researchers, institutions, archives and portals. To use these data effectively, these need to be organised into consistent Merged Observatory Data Files (MODFs). Such an effort is ongoing as part of the World Meteorological Organization's Year of Polar Prediction (YOPP). Initially efforts will focus on the YOPP special observing periods (SOP1: Feb–Mar 2018, and SOP2: Jul–Sep 2018, SOP–Southern Hemisphere: Nov–Feb 2018/19) and the MOSAIC year (Sep 2019 to Sep 2020).

A prototype MODF has been produced for one INTERACT station, Utqiagvik (formerly known as Barrow) Alaska, by the US National Oceanic and Atmospheric Administration (NOAA), and a team has been assembled to begin producing these for other sites according to this template. Once completed, it is expected that the MODFs produced for the polar observatories will provide a valuable resource for benchmarking NWP and climate models, from a process perspective, for many years to come. Further model evaluation using these is planned in the next part of ECMWF's contribution to INTERACTIII.

However, to really be of use for ongoing NWP development, which usually performs testing of new model developments on simulations covering the last year, data need to be made available in an ongoing basis, with only a short lag before they are available for use.

To facilitate process understanding and climate monitoring an extension of the MODF concept to produce Climate Data Records (CDRs) for a wide range of parameters, would be hugely beneficial. Then one would know differences between conditions today and those 10-years ago (e.g. Fig 9) are not an artefact of changes in recording practices or changes in instrument location.

8. References

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