Results in Engineering 3 (2019) 100030

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.editorialmanager.com/rineng/Default.aspx

Enhanced large-scale atmospheric flow interaction with ice sheets at high model resolution

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ARTICLE INFO

Keywords:
Geophysical flow
Numerical simulations
Ice sheets
Atmospheric boundary layer

ABSTRACT

The development in supercomputing power allows running full-complexity Earth System Models (ESM) at increasingly higher spatial resolutions on a global scale. We show here a recent example where increased model resolution leads to a fundamentally different large-scale fluid dynamical adjustment of the mean wind pattern to the presence of an ice sheet over Europe compared to a coarse resolution simulation. While the higher resolution allows for a more realistic representation of atmospheric flow interaction with complex topographic features, the interpretation and prediction of the model results with a stronger bottom-up mechanical and thermal forcing on the atmosphere becomes increasingly difficult to be studied within a fully coupled model. We emphasize that interdisciplinary approaches should be pursued where the experience from engineering approaches of studying flow around objects and the influence of boundary-layer processes can help to disentangle the complexity within ESM. Ultimately, such engineering approaches will add a more fundamental theoretical understanding and prediction of expected flow interactions and will help to design full-complexity atmospheric model experiments accordingly.

Introduction

Large continental-scale ice sheets play a key role in the climate system and their shrinking or growing is known to exert significant ice-sheet-climate feedbacks [2]. In addition, ice sheet height was found to impact the ocean overturning circulation during glacial times (e.g. Refs. [3,9,18]). Several studies have demonstrated that topographic elevation changes will at some point start to act as barrier for the mean flow. As an example, the massive North American ice sheet during the glacial caused a deflection of the large-scale storm track towards the Arctic with strong climatic impacts on high latitudes [12,16]. At the same time, the evolution of ice sheets, their impacts on the climate and uncertainties regarding the size and height of continental ice sheets make it difficult to fully determine climate changes on glacial-interglacial timescales.

So far, millennial-scale global simulations have been run at relatively coarse spatial resolutions. In a recent study, snapshots from a previous transient but coarse-resolution (~400 km, 3.75° × 3.75°) climate simulation of the last 22,000 years (TraCE-21k, [4]) were repeated with the full-complexity Community Earth System Model (CESM1.0.5) at considerably higher spatial resolution of around 100 km (0.9° × 1.25°) for two late glacial periods [15]. Although the background climate with ocean temperatures, sea-ice extent and radiative forcing were identical to the previous coarse-resolution simulation with CCSM3 [4], the high-resolution simulation with CESM1 produced a fundamentally different large-scale wind pattern over Eurasia in response to the comparably smaller Fennoscandian Ice Sheet (FIS) over Northern Europe. As a result of the blocked zonal (westerly) flow by FIS during summer, the new simulation suggests persistently warm late glacial summers across Eurasia [15] while a strong cooling is predicted by the coarse-resolution simulation during periods of strong North Atlantic Ocean cooling. Furthermore, the finer simulation suggests that continental ice sheets create their own wind regime which can fundamentally change the large-scale atmospheric circulation on subcontinental to continental scale.

While it is possible to decompose different changes and contributions of the flow and the related re-distribution of heat in response to a given ice sheet configuration (e.g. Ref. [12]), it is virtually impossible to separate the fluid mechanical changes from the near- and far-field interactions within the fully coupled climate model. An additional difficulty encountered when predicting changes in response to ice sheet configurations arises from the non-linear coupling of mechanical and thermal forcing of ice sheets (e.g. Ref. [14]).

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https://doi.org/10.1016/j.rineng.2019.100030
Received 31 May 2019; Received in revised form 25 June 2019; Accepted 8 July 2019

This article is intended to give a brief perspective on some recent breakthroughs simulating complex flow problems and is organized as follows: In section 2 we provide a brief description of the type of high-fidelity flow simulations that can help to gain insight into these processes; in section 3 we discuss high-resolution CESM simulations, which clearly illustrate the blocking effect caused by the ice sheet; and finally in section 4 we provide an outlook and highlight the most relevant directions of future work.

Direct numerical simulations of flow – resolving all the scales

To gain a more fundamental understanding of expected fluid dynamical changes to certain ice sheet configurations as large obstacles, there is a high potential to investigate such questions with off-line simulations with reduced complexity but increased resolution. High-resolution limited area models (regional climate models) with lateral forcing from a global climate model show that some aspects of near-surface flows over ice sheets like katabatic winds can in principal be reproduced even without resolving all the small scales (e.g. Ref. [8]). However, simulations of stably stratified flows in the atmospheric boundary layer are still difficult although there have been successful attempts to develop less parameterized solutions like explicit algebraic Reynolds-stress and scalar-flux models which show reasonable agreement with direct numerical simulations (DNSs) (e.g. Refs. [10,11]). Note that in DNS, the Navier–Stokes equations are solved numerically with sufficient resolution to resolve all the relevant flow scales. This approach provides a very accurate representation of the flow, as discussed in the seminal work by Ref. [7]. Such models have, however, not yet been used to study complex flow problems typically encountered in global climate or atmospheric models and it remains unclear how improvements of boundary-layer processes might feedback on the large-scale flow.

An interesting test case would hence be to evaluate modified DNS cases mimicking flow around ice sheets with and without the inclusion of boundary layer processes. For instance, Ref. [17] conducted direct numerical simulations, where all the relevant flow scales are resolved, to characterize the flow around a wall-mounted square cylinder. The level of detail of such a simulation can be seen in Fig. 1, where all the relevant coherent structures in the turbulent wake can be observed. This study reflects the complex mechanisms arising from the adverse pressure gradient induced by the obstacle, the incoming turbulence, the formation (and modulation) of a horseshoe vortex around the obstacle and the multi-scale character of the wake.

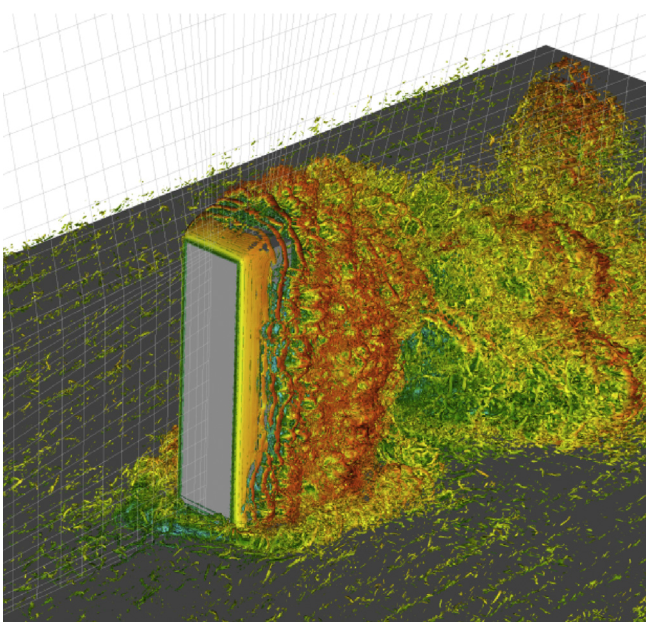

Fig. 1. Direct numerical simulation of the flow around a wall-mounted square cylinder. The figure shows an instantaneous flow field representing vortical structures, identified through the λ_2 method [6]. The colour indicates streamwise velocity, where dark blue and dark red denote low and high speed, respectively. The spectral-element mesh is shown in grey, but not the individual grid points within the mesh. Figure obtained from the database by Ref. [17]; considering a turbulent inflow.

Note that although this particular case developed on a flat plate, a number of strategies have been proposed in the literature to simulate the atmospheric boundary layer (ABL) developing on realistic terrain [1]. There is a strong need to implement such boundary-layer processes in DNS for both, engineering applications as well as to study geophysical flow problems. As shown below for the climate model, the inclusion and realistic simulation of ABL processes is crucial for incorporating the non-linear coupling of mechanical and thermal forcing on the flow. Moreover, high-quality experimental measurements have also been employed to assess the complex interactions between the ABL and arrays of obstacles [13], including the impact of the angle of incidence on arch vortices and the characteristics of gusts. We believe that additional detailed studies of such interactions will provide important insight on the ABL interaction with ice sheets and how these interact with the large-scale flow field. Such simulations will allow to disentangle the different interactions acting on different scales and how these depend on the obstacle design and background state of the flow.

Large-scale blocking and stable boundary layer processes over the ice sheet in a climate model

In a recent study by Ref. [15], snapshots of extreme climate states during the late glacial were simulated with a high-resolution version ($0.9^\circ \times 1.25^\circ$, ~100 km, finite volume grid with 26 levels in the vertical direction) of the full-complexity Community Earth System Model (CESM1.0.5). The model version is a state-of-the-art configuration and has been validated for different applications including climate simulations for the deep past (see references in Ref. [15]). For this project, the model boundary conditions were adjusted to incorporate low sea-level stands and the presence of large continental ice sheets over North America, Scandinavia and the Arctic consistent with geological evidence. The 4x higher model resolution compared to a previous simulation with CCSM3 [4] did not only yield a regionally more detailed climate but also a fundamentally different large-scale response [15] due to a much more realistic representation of the fluid dynamics around large ice sheets.

As shown in Fig. 2a, the roughly zonal (westerly) flow over the North Atlantic towards Scandinavia is blocked by FIS over Northern Europe inducing meridional flow to the north or south. Without FIS or at a too coarse model resolution (Fig. 2b), Europe would be dominated by zonal mean flow as in the modern climate.

As shown in Ref. [15], the blocked flow by FIS dominates during summer while a seasonally stronger zonal flow prevails during the rest of the year during the late glacial. Conceptually, the flow problem over FIS can be described by the *Froude number* F_r which is defined as the ratio of the perpendicular horizontal wind speed U [m/s] relative to the height h [m] of FIS scaled by the vertical atmospheric stability N [s^{-1}] (the *Brunt-Väisäla-frequency*):

$$F_r = \frac{U/h}{N} \text{ (Froude number)} \tag{1a}$$

$$N = \left(\frac{g}{\theta}\frac{\delta\theta}{\delta z}\right) \text{(Brunt-Väisälä-frequency)} \tag{1b}$$

$$\theta = T\left(\frac{p_0}{p}\right)^{\frac{\beta R_L}{C_p}} \text{(Potential temperature)} \tag{1c}$$

Note that in equation 1b g = gravity [m/s^2], θ = potential temperature at surface [K], $\delta\theta$= potential temperature difference [K] for a given

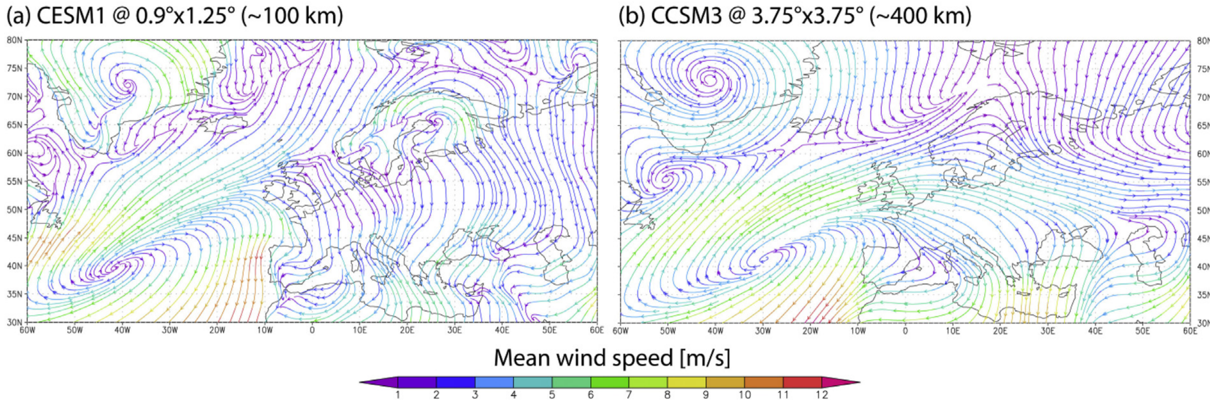

Fig. 2. Example of 100-year averaged monthly mean wind speeds and corresponding streamlines for July for the late glacial (12.000 years ago) as simulated with the (a) high spatial resolution model version of CESM1 and (b) low resolution model CCSM3. Note the fundamentally different flow (streamlines) over Europe in the high resolution case (a) with blocked flow downstream of 10° E while in (b) zonal flow dominates in the low resolution case. The blocked flow causes considerably warmer summers during the late glacial (consistent with geological evidence, [15], while the zonal flow would result in too cold summers. Figure derived from the data by Ref. [15]. See Fig. 3 for a more detailed characterization of flow over the ice sheet for CESM1.

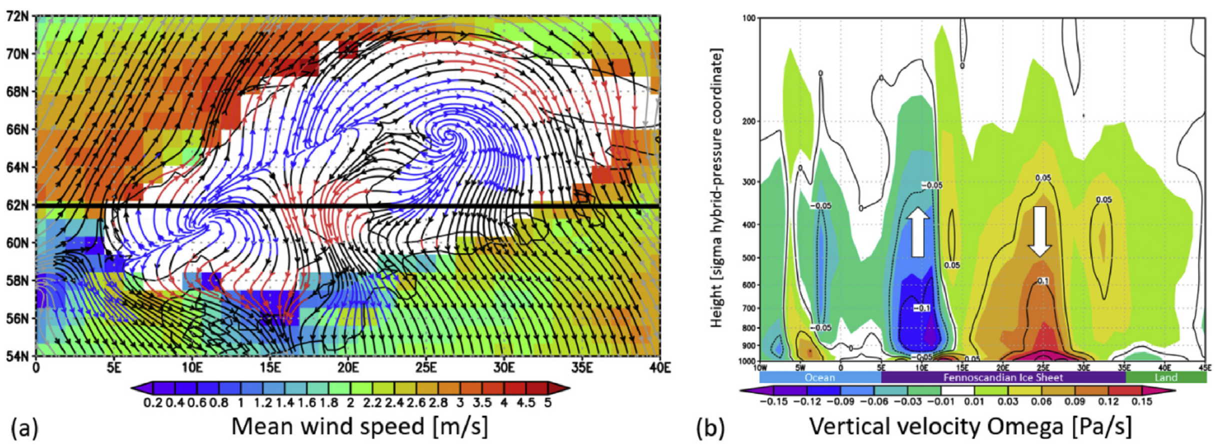

Fig. 3. Examples for the modulation of horizontal (a) and vertical (b) flow caused by the Fennoscandian Ice Sheet (FIS) for July during the late glacial. The anticyclonic flow over the ice sheet (a) results from katabatic winds which develop within a very stable boundary layer over the ice and accelerate downslope. Strong divergence on the plateau highlighted by blue streamlines are linked to descending air flow over the ice sheet (b, positive Omega). Although there is substantial orographic lift over the western part of FIS around 10° E (b, negative Omega), it does not extend across more than half the diameter of FIS so that the flow is deflected horizontally to the north or south (a). The blocking of zonal flow (Fig. 2a) by the ice sheet results from a nonlinear interaction of mechanical forcing and thermal forcing which induces a strong near-surface thermally driven anticyclone. The vertical flow (b) is shown here for a zonal west-east cross section through 62° N (black line in (a). The database for the figures is the model experiment clim12k from Ref. [15].

δz = elevation difference [m]. The potential temperature θ in equation 1c includes T = absolute temperature [K], p_0 = reference pressure [Pa], p = pressure at elevation h [Pa], $\beta = 1$ for dry adiabatic (otherwise $\beta < 1$), R_L = specific gas constant (dry air) [J/(kg K)]; c_p = specific heat capacity of air for p = const [J/(kg K)].

In summer, lower mean wind speeds U will increasingly fail to cross FIS for a given height h leading to increased seasonal blocking on a larger spatial scale ($F_r < 1$ in Eq. 1). In addition, very cold North Atlantic Ocean temperatures during the late glacial upfront of FIS will cause a stronger vertical atmospheric stability N (Eq. 1b) which virtually increases the barrier height h relative to the perpendicular flow U against FIS. The increased vertical stability impact on the flow over FIS is also captured by the CESM1 simulation where a colder ocean state leads to increased blocking by FIS and slightly warmer summers [15].

However, a more detailed analysis of the wind field over and around FIS (Fig. 3) suggests that the blocked flow is more complicated than simply a deflection of the flow due to mechanical forcing by a large barrier. The failure of the coarse-resolution model to simulate the blocking (Fig. 2b) may hence not only result from a horizontal and vertical smoothing of the topographic height of FIS but also from a too unrealistic representation of near-surface atmospheric boundary processes over ice – the establishment of a very stable atmospheric boundary layer (SBL).

In general, large continental ice sheets with areas of >100 km^2 to >1000 km^2 with relatively smooth homogeneous surfaces are known to build up a very stable boundary layer (e.g. Ref. [5]). The vertical temperature profile typically shows a strong inversion layer over the ice surface which continues also downslope. Because the heat loss of air over ice is strongest at the surface, the pressure-gradient force is strongest in the lower SBL. However, friction reduces the wind speed at the ice surface resulting in a highly turbulent but vertically restricted lower SBL. In the mid-SBL, the downslope pressure gradient is still large but friction is low so that katabatic winds reach their maximum speeds with a gravitational acceleration of the cold and dense air downslope. At the upper SBL, the wind becomes quasi-geostrophic. Due to Coriolis forcing, the downslope wind rotates to the right with increasing height (Fig. 3a), causing a clockwise anticyclonic rotation over large ice sheets. Although the climate model does not resolve the turbulent lower SBL in detail, the inversion layer (not shown) and anticyclonic rotation (Figs. 2a and 3a) of the downslope wind is clearly reproduced by CESM1 close to the ice sheet. While synoptic disturbances like cyclones or frontal systems moving over the ice sheet will temporarily destroy the SBL, the SBL processes are clearly dominating and the anticyclonic near-surface wind pattern is clearly visible even as a 100year mean state as illustrated here for July (Figs. 2a and 3a).

Idealized studies of orography-induced flow disturbance have shown that the coupling between mechanical and thermal forcing is non-linear [14]. In case of ice sheets, the low-level cooling over ice tends to amplify the mechanical forcing and increases the large-scale disturbance of atmospheric flow. Increasing the spatial model resolution from ~400 km (CCSM3) to ~100 km (CESM1) appears to strongly increase the bottom-up forcing of boundary layer processes. At the same time, the question arises if such a blocking effect would become even stronger if the model resolution would be further increased given the non-linear coupling to cooling over ice. Ultimately, this raises the question how different the flow modulation would be if all scales of the SBL could be resolved like in a DNS.

Outlook

In this perspective article we showed recent examples for the advancement in modelling geophysical flow disturbance by large ice sheets in a high-resolution global climate model and complex flow features around an object by means of DNS. While increasing model resolution allows to study flow at a higher level of detail, challenges to understand and predict the modelling outcome arise from the full-complexity of the involved processes acting across different scales (as in Earth System Models) or the question how the results from resolving all scales in a DNS may change from adding complexity like e.g. a step-wise inclusion of different boundary-layer processes. In the context of climate modelling at increasingly higher resolution, there will be an enhancement in the bottom-up forcing of small-scale processes onto the large-scale flow patterns. It can be expected that classical fluid mechanical engineering applications will be more widely used in the context of climate modelling, in order to address the question of how small-scale processes interact and/or modulate large-scale processes in complex systems.

Declaration of interests

The authors declare no conflict of interest.

Acknowledgements

The climate model simulations with CESM1 and the DNS were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at Linköping University and PDC at KTH Stockholm. The CESM project is supported by the National Science Foundation and the Office of Science of the U.S. Department of Energy. TraCE-21ka was made possible by the DOE INCITE computing program, and supported by NCAR, the NSF P2C2 program, and the DOE Abrupt Change and EaSM programs. Funding for F.S. was provided by the Swedish Nuclear Fuel and Waste Management Company (SKB) in cooperation with the Linné FLOW Centre at KTH Stockholm and the Bolin Centre for Climate Research at Stockholm University. F.S. received additional funding from the Swedish Research Council (VR 2015-04418).

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