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ЭФФЕКТЫ, ОБУСЛОВЛЕННЫЕ УСТОЙЧИВО-СТРАТИФИЦИРОВАННЫМ ПЛАНЕТАРНЫМ ПОГРАНИЧНЫМ СЛОЕМ В КЛИМАТЕ СЕВЕРНОГО ПОЛУШАРИЯ ЗЕМЛИ

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Планетарные пограничные слои вносят определенный вклад в формирование и поддержание климата Земли. Глубокая проникающая конвекция и конвективное приспособление охлаждают планету и контролируют гидрологический цикл. Поэтому конвективные процессы активно изучаются климатологами. Напротив, тонкий устойчиво-стратифицированный пограничный слой получает значительно меньше внимания, поскольку его влияние связывают, главным образом, с местными особенностями климата. Настоящее исследование демонстрирует значительное влияние устойчиво-стратифицированного пограничного слоя на глобальный климат Земли. В данной работе, устойчиво-стратифицированный пограничный слой идентифицируется как ведущий фактор, модулирующий отклик в приземной температуре воздуха на аномалии климатического теплового баланса. Области с наибольшими величинами многолетних температурных трендов и наибольшей температурной изменчивостью географически совпадают с областями, в которых тонкие устойчиво-стратифицированные пограничные слои встречаются часто. Линейные коэффициенты корреляции между обратным значением толщины устойчиво-стратифицированного пограничного слоя и приземной температурой воздуха достигают значений 0.4—0.6 над Евразией и морскими льдами Арктики. Особенно сильные корреляционные связи найдены для континентальных климатов Сибири, где влияние влажности почвы и облачности менее выражено. Климатические модели несовершенны в части расчета свойств устойчиво-стратифицированного пограничного слоя. Это приводит к появлению систематических отклонений моделей при расчете климатических трендов температуры и краткопериодной температурной изменчивости.

Ключевые слова: планетарный пограничный слой, климат, температура приземного воздуха, энерго-балансная модель, устойчиво-стратифицированная турбулентность.

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STABLY STRATIFIED PLANETARY BOUNDARY LAYER EFFECTS IN NORTHERN HEMISPHERE CLIMATE

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Planetary boundary layers contribute to the shaping and maintaining of the Earth's climate. The deep penetrative convection and convective adjustment cool the planet and controls the hydrological cycle. Hence, the convective processes are intensively studied by climatologists. By contrast, the shallow stably-stratified boundary layer receives much less attention. Its impact is mostly associated with local climate features. This study demonstrates that the stratified boundary layer has significant impact on the global earth's climate. The study identifies the stably-stratified boundary layer depth as a leading factor modulating the surface air temperature response to anomalous climate heat balance. Geographically, the regions with the largest surface air temperature trends and variability are collocated with the regions where the shallow stably-stratified boundary layers frequently occur. The linear correlation coefficients between the inverse stably-stratified boundary layer depth and the surface air temperature reach 0.4—0.6 over Eurasia and the Arctic sea ice. Particularly strong correlations are found for the continental climates over Siberia where the impacts of soil moisture and cloudiness are less pronounced. Climate models do not adequately represent the depth of the stably-stratified boundary layer which results in systematic model biases both in climate temperature trends and in short-term temperature variability.

Key words: planetary boundary layer, climate, surface air temperature, energy-balance model, stably stratified turbulence.

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The Earth's climate is shaped not only by the balance of radiative heat fluxes but also by the atmospheric and ocean dynamics. The roles of planetary scale dynamics and convective vertical mixing (in the form of a radiative-convective equilibrium) have been recognized since the early days of climate science, whereas the climate effects of the shallow stably-stratified atmospheric boundary layer (SBL) is still to a large degree overlooked [1, 2]. Indeed, the atmospheric turbulent convection significantly contributes to atmospheric dynamics on a multitude of scales ranging from the very local ones up to the planetary scales [3]. It was and still remains a topic of high interest for the climate modeling community [4—6], whereas the climate role of the atmospheric SBL has received much less attention [7].

The shallow SBL, being the part of the climate system with the least inertia, quickly adjusts to the free troposphere and soil conditions. Thus, the SBL can have a climate effect only through selective and asymmetric contribution to the climate statistics. We illustrate this effect with a conceptual bulk energy-balance model [8, 9]

$$dT/dt = Q/h. \tag{1}$$

Here, Q is the kinematic heat flux divergence across the boundary layer, T is the surface air temperature (SAT), and h is the boundary layer depth, i. e. the thickness of the layer closest to the ground that is characterized by strong vertical turbulent mixing. Detailed mathematical analysis of the model in Eq. (1) with respect to Q and h variability can be found in [8, 10, 11]. Here, we are primarily interested in statistical analysis of this model with respect to the observed climate variability and trends. Considering the SAT response to a given perturbation of the climate forcing, one can notice that the SAT response should be larger in more shallow boundary layers. Hence, if the boundary layer depth is a climatologically important parameter, we should find a significant correlation (regression) between h^{-1} and dT/dt on the climate-relevant time scales.

In the Earth's climate, both Q and h are highly variable and their fluctuations frequently demonstrate high correlations. More dense cloud cover, higher surface albedo and higher soil moisture significantly perturb Q with statistically significant effects on the SAT [12—14]. However, those effects correspond to the climate conditions with the positive surface heat flux $Q > 0$. These conditions are robustly associated with the diurnal/seasonal maximum temperatures $T_{\max}$ [15, 16]. By contrast, the statistical analysis of the SAT climatology revealed that the largest changes and variability are observed in the diurnal/seasonal minimum temperatures $T_{\min}$ [17—19]. The minimum temperatures are robustly associated with the SBL conditions where $Q < 0$. The larger climate response found in $T_{\min}$ requires a new look at the turbulence dynamics and controlling factors that govern the SBL.

A crucial contribution in developing a new understanding of the SBL processes, their control factors, and the mechanisms working at the climatological time scales has been given by Sergej S. Zilitinkevich. For decades, since the introduction of the first Businger-Dyer and Louis SBL closure schemes [20], boundary layer meteorology was facing a paradox that significant turbulent mixing could be still observed in super-critical Richardson number conditions. Several attempts to resolve this paradox resulted in physical inconsistencies or even in unexpected multi-regime transitions in the turbulence closures [10, 18]. Because the cessation of turbulence mixing threatens the numerical stability of the boundary layer schemes in climate models, engineering solutions — either the non-zero minimum eddy viscosity, or artificially weak stability correction functions — were implemented [7].

Using new field data sets and numerical large-eddy simulations, Zilitinkevich and co-authors have showed in a series of works [21—23] that the SBL depth does not collapse in the long-lived stably-stratified layers. This finding indicated that the SBL turbulence mixing remains an important climate-shaping factor, and that the energy-balance model for the SAT cannot be reduced to the sum of radiation and soil heat fluxes. In the following works, Zilitinkevich and co-authors specified a dynamical mechanism — the turbulent kinetic energy conversion to the turbulent available potential energy [24] — to explain the turbulence mixing in the strongly stratified SBL. Moreover, they proposed a new hierarchy of energy-flux balance turbulence closures to recover the correct SBL description in the atmospheric circulation models [25, 26].

The reviewed literature demonstrates a considerable progress in our understanding of the climate effects related to the energetics of turbulence in the stably-stratified boundary layer flows. This study looks back from the SBL physics to the geography of the SBL climate effects. We discuss the geographical areas where the climate is dominated by the SBL conditions. The study characterizes the SBL climatology and the asymmetry of the SAT response in those areas. Finally, it presents the SBL depth dependence in the Eurasian and Arctic regions. The study has the following structure. The next section describes the data and methods. Section 3 presents the results. Section 4 outlines the discussion and conclusions.

Data and methods. We used three types of data sets in this study: the Climate Research Unit (CRU) gridded temperature data; the temperature data from meteorological stations; and the reanalysis data.

The observation dataset 'CRU TS 3.10.01', produced by the Climate Research Unit (CRU) is available at http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276. This dataset includes monthly means of the daily temperature minimum, mean, and maximum. The temperatures are merged onto a 0.5×0.5 degree grid from over 4000 weather stations worldwide, covering the period 1901—2009. We utilize the last 50 years (1960—2009) of the time series extracted from the dataset.

For the correlation analysis we required a dataset which included boundary-layer depth and the SAT, and so we chose the ERA Interim reanalysis product. We extracted the monthly-mean time-series from the ECMWF website for the full-period of available data, 1979 to 2015. The virtual potential temperature at a height of 2 m above the ground was calculated and used in our analysis. The boundary layer depth in the ERA-Interim model was calculated using an iterative bulk-Richardson method which scans upwards from the lowest model level and interpolates between model levels to find the height at which the bulk Richardson number first exceeds the critical Richardson number, taken to be 0.25.

The SAT variability and trends were obtained as follows: Monthly anomalies were calculated by removing the average of the full-period of the time series for each month from the time-series of each variable. The trends were computed using a least-squares linear regression, with the trends filtered for significance at $p < 0.05$. The regional means of the anomaly time series were created by taking the area-weighted-mean of grid points within the region.

Results

Structural climatology of the SAT. Given the structure of the climatology of the SAT we can understand the differential changes in the diurnal temperature extremes T_{min} and T_{max}. The diurnal mean SAT is often computed through averaging of the temperature extremes as $(T_{min} + T_{max})/2$. Hence, if the changes in the diurnal maximum temperature are damped by a large h in the convective boundary layer in eq. (1), then the expected contribution of T_{max} changes to the overall SAT change would be small.

Statistical analysis of the CRU gridded data reveals that the observed SAT trends over the northern continents are geographically and seasonally inhomogeneous. Unfortunately, the state-of-the-art climate models misrepresent even the continental-scale patterns in the trends [27]. The strongest annual and seasonal (with exception of summer) SAT trends are observed over continental Eurasia, and particularly over Siberia. Although the seasonal trends vary considerably over many regions, the trends over Central Siberia remain consistently strongly positive reaching 0.3—0.6 K dec^{-1}.

The structural climatology of the SAT trends is shown in fig. 1 (see an insert). One can observe that the trends in T_{min} (fig. 1, *b*, *c*) are significantly larger than the corresponding trends in T_{max} (fig. 1, *a*, *c*) in many regions. Particularly large differences are observed over the territory of the Russian Federation. Both diurnal extreme temperatures increase in winter and summer seasons, but their increase in the summer is significantly smaller, reflecting the deeper boundary layers in summer. These differential changes are more clear in the analysis of the diurnal temperature range (DTR), which is defined as DTR = $T_{max} - T_{min}$ (fig. 1, *e*, *f*). The negative DTR trends indicate that T_{min} was rising more rapidly during the considered 50 years period.

Comparison of the SAT structural changes showed that the continental climate of Siberia, and particularly of Central and Eastern Siberia, has warmed mostly because of the quickly rising T_{min}. This is the expected response on the uniform anthropogenic warming in a climate with large diurnal and seasonal variations in the boundary layer. The temperature rise in Europe and North America was more even, although T_{min} is rising somewhat faster than T_{max} in those regions too.

The SBL depth climatology. The sub-section above presented the structural analysis of the SAT, i.e. the left-hand side of eq. (1). If one assumes that the global warming is dominated by the large-scale uniform climate forcing, then the geographical and seasonal variations in the boundary layer depth should be included in any explanation of the patterns of SAT change. Fig. 2 (see an insert) shows the SBL depth and frequency climatology from the ERA-Interim reanalysis data (1979—2014). Generally, the areas of high SBL frequency are in good agreement with the areas of the largest difference between the diurnal extreme trends (the DTR trend), as well as with the areas of the largest trends and the largest SAT variability. Nevertheless, Fig. 2, *b* shows us that the association between the magnitude of the SAT trend and the SBL depth is rather loose.

The reader should note that the structural trends are determined not so much by the absolute value of *h* as by the difference in the boundary layer depths at the times when T_{min} and T_{max} occur. Hence, the diurnal temperature extremes due to air mass advection, cloudiness and precipitation will reduce the statistical correspondence expressed in eq. (1). Moreover, the fact that *h* is in the denominator makes T_{min} much more sensitive to occasional heat forcing perturbations. This statement can be quantified by statistical analysis of the SAT. The high sensitivity of lower temperatures means that there should be an anti-correlation between the mean SAT and its standard deviation. Fig. 3 (see an insert) shows that such strong anti-correlations are found on the intra-annual time scales over the continental areas and the ice covered Arctic Ocean. Note that the SAT trend is just the longest mode of climate variability. The larger T_{min} changes occur not only, and maybe not even, because of larger climate forcing efficacy in the shallower layer, but also because the deeper and more inertial layers do not rapidly respond to variations in the external forcing.

Regionally aggregated SBL depth effect. The proposed SBL effect provides only a complementary explanation to the observed temperature variability. The climate forcing *Q* is also modified by the soil moisture, land use — land cover and cloud changes. However, the SBL effect could overwhelm the other effects and feedbacks when h becomes small. How small should the mean h be to make the linear regression $dT/dt \sim (h)^{-1}$ dominant over the other effects?

We answered this question in the following way. The SAT trends in larger regions (Eurasia and the Arctic) were binned according to the mean h in the corresponding grid cell. Thus, all trends from the grid cells with, say, 100 m deep SBL are placed in the same bin. Then for each bin, the mean and standard deviation are computed. The results are presented in fig. 4. Over the Arctic region where the shallow SBL dominates over the whole year, the SBL depth is the major factor scaling the efficacy of the climate forcing. Here, the correlation coefficient between h^{-1} and dT_v/dt is 0.4, distinguishable from the «absence of linear correlations» hypothesis at $p < 0.01$. The dependence over the Eurasian region consists of two segments. The shallow SBL segment (*h* is less than 500 m) exhibits the correlation coefficient between h^{-1} and dT_v/dt is 0.45. The deep convective boundary layer segment with $h > 500$ m does not exhibit any significant boundary layer depth dependence, suggesting a larger effect of the heat forcing variations due to other climate factors.

Discussion and conclusions. The widely recognized bulk energy-balance climate model in eq. (1) suggests that the observed temperature changes should be caused by perturbations in the climate heat forcing and modulated by the depth of the boundary layer. The SAT sensitivity to the perturbations and feedbacks in the climate forcing was studied extensively, whereas the role of the turbulent mixing in the boundary layer was largely overlooked. Moreover, the emerging evidence of the SAT modulation by the SBL effect was often misinterpreted as effects of clouds, land cover and soil moisture. Partially, this development could be explained by the modeler's way of thinking. The boundary layer depth is normally not included in the planetary boundary layer schemes as an external parameter with which to be experimented. However, vegetation, soil thermodynamics and cloud processes have convenient parameters which are easy to modify and to see an effect in the model run inter-comparison.

Let us consider for example an analysis of a very large ensemble of model sensitivity experiments. Knight et al. [28] demonstrated in their analysis of an ensemble of 57 067 HadAM3 climate model runs that 80 % of variation in climate sensitivity to doubling of CO2 could be traced down to a small subset of atmospheric convection parameters. The most influential parameter (32 % of the total variability) appeared to be the turbulent entrainment rate. Thus, they pointed out the importance of the cloud formation processes and called for improvement of the cloud parameterizations. Their results could be re-interpreted to take into account the boundary layer depth effect. The entrainment rate is a parameter that controls the boundary layer depth in the convective parameterizations. In this sense, one third of the model climate sensitivity in those experiments should be attributed to the variations in *h*.

It is useful to compare this study and results from Esau and Davy [16] with the regional study [29]. Qu et al. also found a steady decreasing trend of DTR over the United States in the past 100 years. The DTRs also show the decreasing rates and seasonal variations. This decrease has become more significant during recent decades. Similar to the trends over Eurasia, T_{max} over the continental USA has a very slightly increasing trend, while T_{min} was rising at a much faster rate. However, the largest structural differences in the SAT trends over USA are found in the summer and fall seasons. This dissimilarity between the North American and Eurasian trend seasonality reflects the impact of the persistent Siberian anticyclone. The anticyclone keeps the SBL

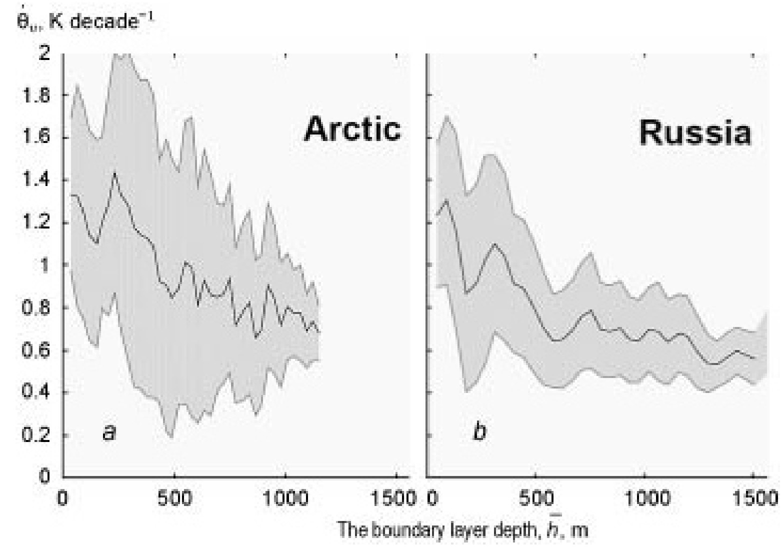

Fig. 4. The regionally integrated dependences between the surface virtual air temperature change and the atmospheric boundary layer depth for Eurasian and Arctic regions.
The dependences were obtained using ERA-Interim reanalysis data (see Section 2) binned according to *h*. The bold line shows the bin-averaged values; shading shows 3 standard deviation intervals ($p < 0.01$) of the inter-grid scatted of the data in the same *h*-bin.

conditions over longer time periods allowing for equilibrium long-lived stably-stratified boundary layers to form, introduced in [30]. Fig. 2, a showed that SBLs are more persistent over Asia than over the other northern regions. Thus, as it has been shown with the statistical analysis in this study, the direct effect of the shallow SBL depth dominates the SAT trends over northern Asia, but the indirect effect of low SBL inertia in response to variable external conditions dominates the SAT trends over Europe and North America.

Finally, this study quantified the conditions where the proposed SBL depth effect emerges over the other climate effects and feedbacks. The statistical correlations between the SBL depth and the SAT trends become significant when $h < 500$ m. In the areas and during time periods where and when the mean climatologic $h < 300$ m, the SBL depth dependence shapes the climate features.

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