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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Regression Models for the Estimation of Carbon Exchange in Boreal Forests

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Abstract—Based on the measurements of the carbon dioxide fluxes at a few sites of the global FLUXNET network, we developed linear regression models for the estimation of the carbon budget of boreal forests. The model estimates satisfactorily agree with the measurement data obtained in the boreal forests of Canada (Manitoba, Thompson) and Russia (Krasnoyarsk krai, Zotino). The correlation coefficient between the calculations and measurements for a coniferous forests exceeds 0.9, with the annually mean model error in the budget estimate, as compared to the experimental results, not exceeding 50 $gC/m^2/yr$. Using satellite and ground-based meteorological data, we calculated the monthly average carbon budget of the coniferous forests of Krasnoyarsk krai in 2001. Based on the satellite classification of the vegetation cover, we plotted monthly and annually average maps of the carbon budget that reflect the spatiotemporal distribution of the CO_2 uptake and emission rates. It is shown that the coniferous forests of Krasnoyarsk krai are mostly a carbon sink, uptaking as much as 300 gC/m^2 throughout the growing season.

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INTRODUCTION

An important stage of monitoring climate change is regular measurements of the carbon budget of forested ecosystems. At present, one of the most important sources of data on the spatial distribution of CO_2 fluxes is the global FLUXNET network [1]; it incorporates over 200 measurement sites in different regions around the globe with special towers. A few of these sites also operate in Russia. The towers are equipped with instruments that measure the carbon dioxide fluxes in the near-ground atmospheric layer by the eddy covariance method [2, 3]. A serious drawback of the measurement sites of the FLUXNET network types is that their organization and use are expensive. This is especially topical for the taiga-covered, vast, sparsely populated territories of Siberia, for which the satellite methods for the assessment of the carbon budget in terms of the Net Ecosystem Exchange (NEE) often are the only possible methods. In this regard, the approach we propose in this paper is aimed at constructing simple linear regressions relating the NEE of boreal forests with the parameters of the atmosphere and the underlying surface, which, in turn, can be inferred from satellite measurements or the accumulated statistics of ground-based meteorological observations.

THE CHOICE OF FIELD DATA OF CO_2 FLUXES AND THE CONSTRUCTION OF REGRESSION MODELS FOR DIFFERENT FOREST TYPES

In order to develop the regression algorithms in the boreal forests of the Northern Hemisphere, we chose the locations where ground-based measurements of the CO_2 fluxes were available. The natural limitations in the site selection were the presence and type of the forest and climate, as well as the duration and continuity of the measurements. At latitudes northward of 45°, we selected four stations with coniferous forests, three with mixed forests, and two with deciduous forests.

The data sources for North America were the results obtained during the implementation of the AMERIFLUX multiyear research project [4]. For Europe, the sources were the results of an analogous project, EUROFLUX [5–7]. In the Asian part of Russia, we chose Zotino, a Central Siberian site, where during a few warm seasons the measurements in the framework of the Western European projects (Terrestrial Carbon Observing System) were conducted. Data of the Zotino measurements are presented in [8, 9] and at the TCOS Siberia website [10].

The selected stations, with an indication of the forest-cover type according to the International Geo-

sphere–Biosphere Programme (IGBP) [11] classification, are listed in Table 1.

Abundant data on the carbon exchange of coniferous forests are obtained from the BOREAS NSA (Canada, Manitoba) research site, which presented one of the longest term (from 1994 to 2003) time series of continuous measurements. The 13-m research tower with the measuring instrumentation was located on the forested terrain of black 100-year spruce, rising 10 m above the tree crowns. The NEE database was compiled using long-term CO_2 flux measurements every half hour [12–14]. The Zotino measuring tower was located in Krasnoyarsk krai west of the Yenisei River [15] in a forest with 50- to 200-year-old pine trees. The CO_2 fluxes were recorded up to a height of 25 m, 5 m higher than the mean crown level [16]. For the coniferous forest model, we used the data of 9-year (1994–2003) BOREAS NSA measurements and 3-year (1999–2001) Campbell River, (1997–1999) Hyytiala, and (1999–2001) Zotino measurements.

THE CONSTRUCTION OF REGRESSION MODELS FOR DIFFERENT FOREST TYPES

The FLUXNET data, in addition to the CO_2 fluxes, present the measurements of up to 50 accompanying meteorological and geophysical parameters, allowing for an assessment of their influence on carbon fluxes. The regression models were constructed based on the selection of the parameters, which were determined/calculated directly from satellite data. The model input data were chosen to be the monthly mean values of the level of photosynthetically active radiation (PAR) (400–700 nm), the precipitation amount Q_m, and atmospheric T_a and soil T_s temperatures.

For the cold period of the year, only the BOREAS NSA data were available. For the warm (from April to October) season, the measurements performed in different continents were integrated into a single database guided by the similarity of the stable climacteric development stage of coniferous forests at all of the selected stations of the boreal zone. The finer differences in the specific ecosystem features were accounted for through the climatic factor.

To retrieve the monthly mean NEE values, the standard linear regression model was constructed in the form

$$y_k = \sum_n b_{k,n} x_{k-\Delta k,n}, \qquad (1)$$

where k is the month number; $\Delta k = 0$–2; $y_k = \mathrm{NEE}_k/\mathrm{PAR}_k$ for $k = 4$–10 and $y_k = \mathrm{NEE}_k$ otherwise, in gC/m^2/day; and $b_{k,n}$ are constant regression coefficients and $x_{k,n}$ are the corresponding regression factors: the constant term $x_{k,0} \equiv 1$, monthly mean precipitation amount Q_m, atmospheric temperature T_a, soil temperature T_s, and climatic factor CF.

The calculations with different CFs showed that the sought factor, satisfactorily connecting the experimental data for stations with an identical forest type into a single regression model, may be the station-specific climatic annually average precipitation amount Q_y. Table 1 presents the annually average precipitation amounts for the stations; the data are borrowed from the Leemans and Cramer Climatic Database [17].

After the regression coefficients (1) were determined for different forest types, the errors were estimated by comparing the NEE calculations with the NEE measurements in all coincident months. For coniferous forests, for which an 18-year dataset was available, the root-mean-square error for the kth month, σ_{mk}, was determined as

$$\sigma_{mk} = \frac{1}{\sqrt{(18-5)}}\sqrt{\sum_{i=1}^{18}\left(\frac{\mathrm{NEE}_{\mathrm{exp}_i} - \mathrm{NEE}_{\mathrm{calc}_i}}{\mathrm{NEE}_{\mathrm{exp}_i}}\right)^2}, \qquad (2)$$

where 18 is the number of observation years, and 5 is the number of the regression factors in (1) without PAR.

For coniferous forests in the Boreal Ecosystem–Atmosphere Study (BOREAS) Northern Study Area (NSA), the error was 0.8 gC/m^2/day for July and 0.2 gC/m^2/day for October. In Zotino, the largest discrepancy was approximately 1 gC/m^2/day in August.

The annual retrieval error σ_y (gC/m^2/yr) was determined as

$$\sigma_y = 30\sqrt{\sum_{k=1}^{12}(\sigma_{mk})^2}.$$

For such an approach, the effective accuracy of the NEE retrieval from the obtained regression dependences was approximately 50 gC/m^2/yr for coniferous forests, 60 gC/m^2/yr for mixed forests, and 100 gC/m^2/yr for deciduous forests.

Figures 1 and 2 illustrate the quality of the obtained regressions. As seen from Fig. 1, the calculated values from the regression models for the entire set of the coniferous forests, $\mathrm{NEE}_{\mathrm{calc}}$, well correlate with the corresponding experimental values: $\mathrm{NEE}_{\mathrm{calc}} = 0.98\mathrm{NEE}_{\mathrm{exp}}$ with the correlation coefficient of 0.91. A comparison of the seasonal variations of the monthly mean NEE values in 2000 for BOREAS NSA (Fig. 2a) and Zotino (Fig. 2b) also showed a satisfactory calculation–measurement agreement.

THE CHOICE AND ESTIMATION OF INPUT REGRESSION PARAMETERS FOR MODEL TESTING

For the testing of the obtained regression, NEE were calculated using independent input parameters at the tower locations and the measured CO_2 fluxes. In this case, the parameters PAR, T_a, T_s, and Q_m were those from the satellite sources of information, climatic data, or ground-based observations.

PAR estimates for different atmospheric conditions [18, 19] were calculated from cloud fractions measured using MODIS spectroradiometers [20] installed on US NOAA satellites. The diurnally mean PAR for the 15th day of a given month was used as a model estimate of the monthly mean PAR (provided that the cloud fraction was constant during that day). The obtained calculation matrix was used to compile the database from which, applying a linear interpolation, we could calculate the monthly mean PAR values for arbitrarily preset geographic coordinates, the month of the year, and surface type.

The temperature in the near-ground atmospheric layer can also be estimated from satellite measurements with a reasonable accuracy. To infer the temperature from MODIS ASCII Subsets for the FLUXNET measurement sites, we derived the interrelation between the MODIS brightness temperatures T_b and the near-ground atmospheric temperatures T_a. A comparison of the annual behavior of the brightness temperatures T_b, determined by MODIS during a nighttime overpass over BOREAS NSA (2001), with atmospheric temperature data T_a immediately in the near-ground layer at that site made it possible to find the quantitative dependence between them:

$$T_{a_k} = T_{b_k} + d_k,$$

where d_k is the lag constant.

This dependence was used to recalculate the MODIS nighttime temperature data for Krasnoyarsk krai forests over the near-surface T_a required for the regressions.

The soil temperatures T_s were inferred from ground-based measurements or climatic data. To reduce the effect of the T_s uncertainty on the error of the NEE determination, the monthly mean T_s were calculated for all years of the observations. For Siberia, the T_s values were borrowed from the Siberia Soil Temperature Station data [21, 22]. In the West Siberian region, five stations (including Zotino) were chosen at different latitudes from 52° to 64° N: Nizhne-Usinskoe (52.3° N, 93.0° E, Krasnoyarsk krai), Toora-Khem (52.5° N, 96.0° E, Tyva), Losinoborskoe (58.5° N, 89.5° E, Krasnoyarsk krai), Zotino (60.5° N, 90.3° E, Krasnoyarsk krai), and Uchami (63.8° N, 96.3° E, Evenk Autonomous District). For each month, the latitudinal T_s dependences were well fit by parabolas, which were used to obtain the T_s data on the 1° × 1° coordinate grid. The precipitation amount Q_m for each of the months was taken from the integrated Global Precipitation Climatology Project database [23].

For the validation of the regression model designed for the assimilation of the satellite data, we estimated the NEE values accumulated during the year; for this, we used MODIS measurements and meteorological data. The calculations were performed for periods when the MODIS overpasses coincided in time with the ground-based carbon flux measurements at the corresponding site; thus, the input regression data could be specified using the MODIS data.

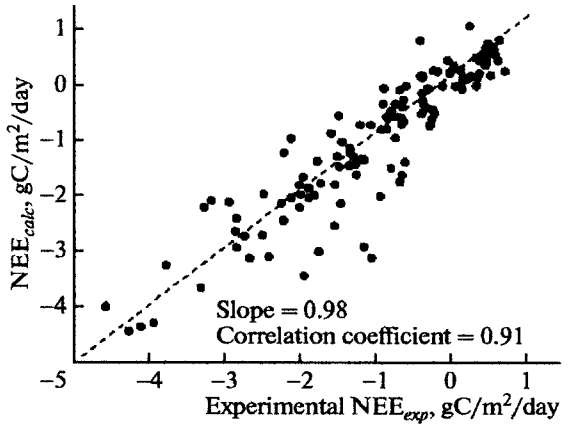

Fig. 1. Correlation between the calculated and measured NEE for evergreen forests.

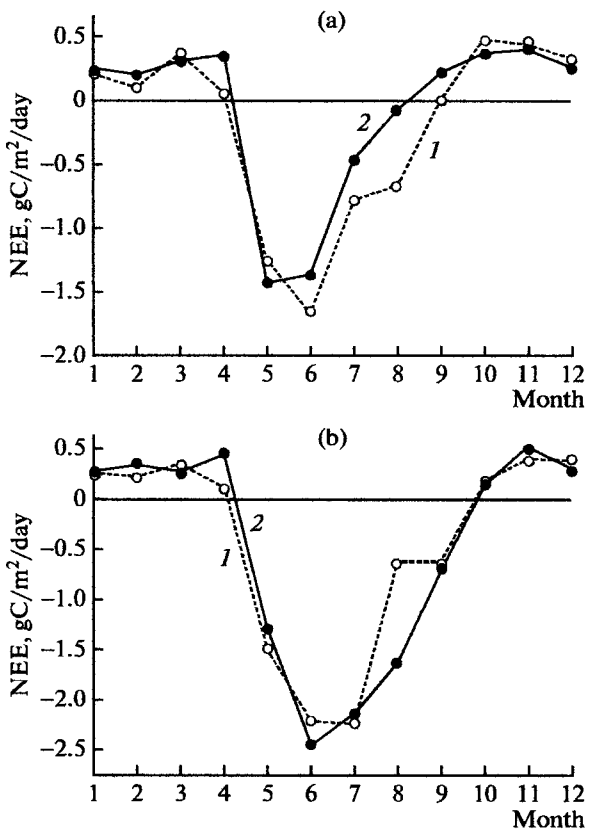

Fig. 2. Comparison of the seasonal dynamics of the calculated (curve *1*) and measured (curve *2*) monthly average NEE in 2000: (a) BOREAS and (b) Zotino.

Therefore, for both observation sites we selected the 2001–2003 measurements for BOREAS NSA and 2000–2002 data for Zotino. The monthly mean pre-

Table 1. List of the selected measurement stations with forests of different types and NEE retrieval errors

Forest type	Station	Coordinates	Observation period used for regressions, yr	Annually average precipitation amount Q_y, mm/yr (climatic factor)	Model error σ_y, gC/m^2/yr
Evergreen needle-leaf forests, IGBP class = 1	BOREAS NSA Manitoba (Canada)	55.9° N, 98.5° W	1994–2003	427	50
	Zotino, Krasnoyarsk Krai, Russia	60.5° N, 89.3° E	1999–2001	621	
	Campbell River, British Columbia, Canada	49.9° N, 125.3° W	1999–2001	1994	
	Hyytiala (Finland)	61.8° N, 24.3° E	1997–1999	569	
Mixed Forest, IGBP class = 5	Vielsalm, Belgium	50.3° N, 6.0° E	1997–1998	847	60
	Michigan, United States	45.6° N, 84.7° W	1999–2002	777	
	Hawland Forest, Massachusetts, United States	45.2° N, 68.7° W	1996–2003	1280	
Deciduous Forest, IGBP class = 4	Willow Creek, Wisconsin, United States	48.5° N, 90.1° W	1999–2003	817	100
	Soroe, Denmark	55.4° N, 11.4° E	1997–1999	548	

cipitation amounts Q_m for BOREAS NSA were extracted from the data of the nearest meteorological Thompson station. The obtained results indicate that the regression-calculated NEE values are in satisfactory agreement with the NEE measurements at both sites.

NEE DETERMINATION IN KRASNOYARSK KRAI FROM GROUND-BASED AND SATELLITE DATA

Krasnoyarsk krai, in the north and south, encompasses several diverse biomes—from tundra and taiga to deciduous forests and steppes. In this regard, before the use of the models, it was advisable to check if a given forest type was present, and also if the possible variations of the natural factors spanned those same limits within which the obtained regression dependences were valid. It was found that at all latitudes, the average T_a, PAR, and Q_m variations were within the model outputs for a coniferous forest. The model for the mixed forest proved to be inapplicable: the T_a values for the conditions of Krasnoyarsk krai were below the T_a range for the European and American sites for which this model was constructed. A comparison of the T_s variability ranges for the measurements and model of the coniferous forest led us to abandon the application of the regression dependence in the southernmost part of the region at 52°–53° N, since the soil temperatures there were higher than the model admitted. Thus, at the given research stage, only the model for the coniferous forest could be adequately applied to the conditions of the region at 54°–64° N, 84°–102° E.

The regression model parameters PAR, T_a, T_s, and Q_m required to calculate the annual NEE budget in Krasnoyarsk krai for 2001 were prepared in the form of a special block of data, each entry corresponding to a 1° × 1° surface grid cell within the region. The dataset included the data on the annually average precipitation amounts Q_a, as well as the approximation-derived T_s values. Calculations using average factors and regression coefficients for the coniferous forest made it possible to obtain the NEE values for individual months and all of 2001.

For the local 1 × 1° Zotino region in 2001, the NEE value was 160 gC/m^2/yr, in good agreement with model estimates [7, 8], which gave the range from −156 to −180 gC/m^2/yr.

PLOTTING THE NEE MAPS FOR KRASNOYARSK KRAI FORESTRIES

To estimate the productivity of the forest massifs and to convert from the formal NEE calculations with the 1° × 1° resolution to a realistic pattern of the carbon exchange, it was necessary to know the distribution of different forest types across the region. We used a map of the Earth's surface of North Eurasia created in the framework of the GLC-2000 project. A map with a 1-km spatial resolution was plotted using the measurements with a VEGETATION sensor installed on the SPOT-4 research satellite. The legend of the map is composed of 27 surface types, defined in obedience to forestry laws and in conformity with the needs of the global climate study [24]. The confidence of the map was assessed through its comparison with the classification data for the Krasnoyarsk krai forestries accessible at the website of the Russian Forestry Department [25]. Table 2 demonstrates the satisfactory agreement between these independent sources in

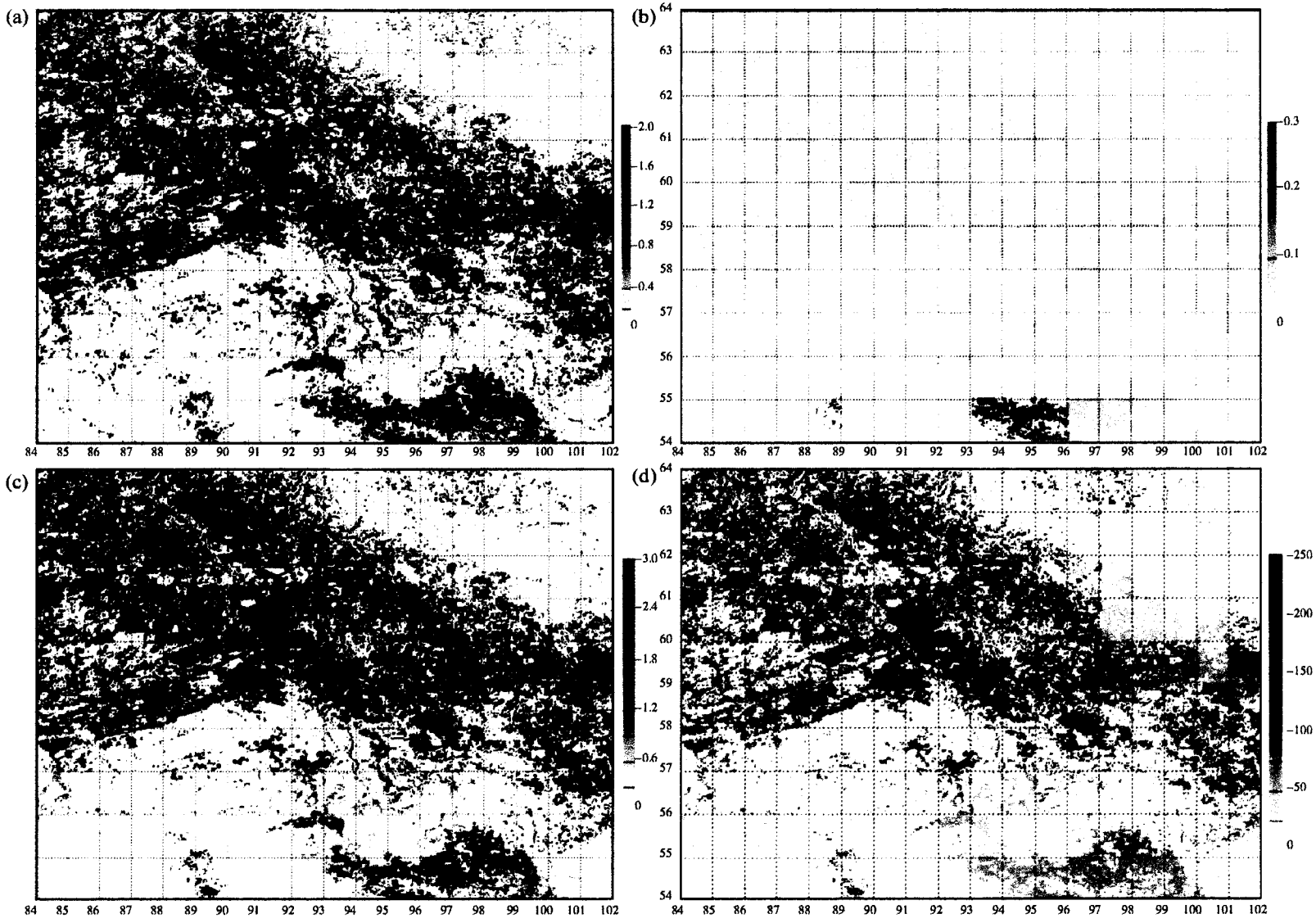

Fig. 3. Carbon budget of the coniferous forests of Krasnoyarsk krai in 2001. Maps of the monthly average NEE ($gC/m^2/day$): (a) May, (b) August, (c) October, and (d) annual ($gC/m^2/year$). Negative NEE (in green) correspond to the carbon uptake by the forest, and positive NEE (October, in pink) correspond to carbon emission.

Table 2. Comparison of relative forested areas according to the GLC map and forestry data

Relative area	GLC map	Nizhne-Yeniseisk forestry
Forested/total area, %	77.8	75.7
Coniferous/total forest, %	85.4	86.4

the Nizhne-Yeniseisk forestry where the Zotino site is located.

This detailed map of the surface types in North Eurasia was used as a cover of the presence/absence of coniferous forest in plotting the real NEE maps obtained from the regression calculations on a 1° × 1° coordinate grid.

The NEE maps (Fig. 3) illustrate the spatial and seasonal distributions of the CO_2 sources and sinks in Krasnoyarsk krai for individual months and the entire year.

Figure 3 provides the pattern of the seasonal variations at different latitudes in the region; it displays the dynamics of the sources and sinks: the same forest fragments may either uptake or release CO_2. With the beginning of the warm season (Fig. 3a), in the southern regions (54° N) the amount of photosynthetically uptaken carbon starts to grow: up to −1.7 gC/m^2/day in May. During this same month in the north (64° N), this characteristic, on average, is not more than −0.5 gC/m^2/day. As the temperature rises, the sinks increase at higher latitudes and decrease at southern latitudes. By August (Fig. 3b), the sinks acquire stronger variations (from −2 to 0 gC/m^2/day) as a function of the local conditions in the south of the region, and a stronger CO_2 accumulation and a greater CO_2 uptake (up to −3.5 gC/m^2/day) take place at more northern latitudes 59°–64° N. In October (Fig. 3c), the growing season ends and, initially at the northern latitudes, the forest ecosystem becomes a weak (+0.6 gC/m^2/day in October) CO_2 source. The calculations suggest that throughout the growing season, most of Krasnoyarsk krai, covered by coniferous forests, is a pure CO_2 sink with a high accumulation rate of up to 300 gC/m^2/yr. The carbon sink is the largest at high latitudes.

In the maps, the shades of green show the CO_2 uptake in accordance with the NEE variations. The darkest shade of green corresponds to the maximum uptake (minimum of NEE). The white color indicates the forest-free regions. The areas in shade-free pink on the map for October (Fig. 3c) indicate weak CO_2 releases. Interestingly, in the southern part of the region (54°–55.5° N, 94°–99° E) there is a characteristic spot of an elevated sink shaped as the Sayan ridge. This may be due to the specific temperature regime of high-altitude mountains.

The plotted NEE maps provide realistic estimates of the distribution of local CO_2 sources. The annual CO_2 sink for coniferous forests (Fig. 3c) is maximal at latitudes of 59°–62° N.

CONCLUSIONS

Based on the FLUXNET data on the CO_2 exchange in forests of the boreal zone of America, Europe, and Asia, we constructed linear regression models to estimate the carbon budget; these models relate NEE gas exchange with the atmospheric parameters and with the state of forested ecosystems. The applicability limits of the model are evaluated.

The model calculations of carbon exchange in boreal forests at the NSA BOREAS (Manitoba, Canada) and Zotino (Krasnoyarsk Krai, Russia) sites demonstrated a satisfactory agreement with the measurements. The NEE values calculated using the regression models for coniferous forests well correlate (0.91 correlation coefficient) with the experimental data. The annually average model error is 50 gC/m^2/yr for coniferous forests and 60 gC/m^2/yr for mixed forests.

Based on the obtained regression model for coniferous forests, using the satellite and ground-based meteorological observations as initial data, we performed calculations of the monthly average NEE values in 2001 in Krasnoyarsk krai. Estimates of the seasonal dynamics of CO_2 uptake (emission) for different latitudes of the region are obtained. Using detailed satellite data on the distribution and types of the vegetation cover, we plotted the monthly and annually average NEE maps, which allowed us to obtain realistic estimates of the distribution of local CO_2 fluxes in Krasnoyarsk krai. The calculations show that throughout the growing season, most of Krasnoyarsk krai, covered by coniferous forests, is a pure CO_2 sink with a high accumulation rate of up to 300 gC/m^2/yr. The annual CO_2 sink rate is the largest at the northern latitudes (59°–62°) of Krasnoyarsk krai.

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