Net Ecosystem Exchange of Carbon Dioxide in Northern Wisconsin

Chanhan Hsu

Abstract

The objective of this report is to identify factors that contribute to the variation of net ecosystem exchange of carbon dioxide. Data contained meteorological factors and ecosystem activities. All variables were recorded on the hourly basis. Only measurements at 12 pm are used in the analysis and missing values are imputed by the mean values.

To consistently estimate the effect of each factor for the time series data with the errors were correlated, I applied the generalized least squares model with a first order autoregressive and a second order moving average structure on residuals.

To investigate the role of soil moisture in the net ecosystem exchange, an ordinary least square linear regression model is fitted to the data from July 2011 to December 2012.

The main conclusions for this report include:

1. The net ecosystem exchange of carbon dioxide associated with the meteorological factors, ecosystem activities, and cyclic factors. The major contributor to net ecosystem exchange is ecosystem respiration and photosynthesis, while meteorological factors such as latent heat, wind speed, precipitation, and water vapor deficit bring about fluctuations.
2. The data do not show evidence that soil moisture is associated with net ecosystem exchange after accounting for ecosystem activities and other meteorological activities.
3. The net ecosystem exchange only relates to time dependent factors via cyclic factor. No increasing or decreasing trend is identified from the analysis.

1 Introduction

Global warming is a popular topic in the media from time to time. With more the carbon dioxide concentration in the atmosphere the less thermal energy that can escape thus an increasing global temperature. The process is known as the green house effect. Environmental scientists for several decades now have been establishing trends between anthropogenic and natural emissions and the global thermal budget by examining carbon cycles and sources and sinks of atmospheric carbon dioxide. In fact, the contribution of human activities to the global carbon cycle is very small, compare with that of vegetation, soil, or ocean. Therefore, understanding the role of vegetation and soil in global carbon cycle would help evaluate the trends between anthropogenic and natural emissions and the global thermal budget.

Respiration and photosynthesis of the vegetation serve as the major contributor of carbon cycle. Soil moisture, along with temperature, and organic matter concentrations is a major player in the rate of soil respiration and the fate and transport of carbon in the environment. In arid desert regions for example where the soil is very dry, microbial activity in soil decreases, conversely in bogs and swamps where the soil remains saturated with water, anaerobic (without oxygen) conditions occur which also affects soil respiration.

This project seeks to understand how the meteorological factors, seasonal factors, and ecosystem activities relate to the net ecosystem exchange of carbon dioxide in north wisconsin. Moreover, the role of soil moisture in carbon cycle is also of interest. The data used in this project are from Chequamegon Ecosystem Atmosphere Study (ChEAS) and collected from multiple sites in mixed forests in Northern Wisconsin from January 1997 to December 2012. The data sets containing 82 hourly measurements for meteorological and ecosystem activities. 18 of the covariates (see Table 3) that best measures meteorological and ecosystem activities are chosen and select the measurements at 12 pm to remove the daily fluctuation. The missing values are imputed by the mean of the same-day measurements from other years.

2 Effects of Meteorological Factors, Ecosystem Activities, and Seasonality

2.1 Model Choice

To evaluate the relationship between NEE and meteorological and seasonal factors, an ordinary least square (OLS) regression model was fitted for NEE against all variables. Variables that account for the periodicity are also included in the model. See Table 7 for a full list of variables.

One problem with the OLS estimates is that the residuals were highly correlated (Figure 4 in Appendix). To capture such correlation structure, I applied generalized least squares (GLS) model for the data. To model the correlation structure of the residuals, I first, applied Augmented Dickey-Fuller test (ADF) to the residuals from the OLS model to test if the residuals were stationary. The test gives a p-value of 0.01, suggesting that there is strong evidence that the residuals follow a stationary process. The slowly decaying pattern of the PACF plot suggests of an moving average pattern. The ACF plot suggests that an autoregressive pattern might be in presence as well. I tried several choice of residual structures, including MA(1), MA(2), ARMA(1, 1), ARMA(1, 2), ARMA(2, 2), and random-walk for the residual. The GLS model with ARMA(1, 2)-structured error was chosen since its residuals had the white noise pattern (Figure 5) and provides a better fit under the AIC.

2.2 Variable Selection

Starting with the full linear regression model with ARMA(1,2) residuals, backward elimination was used to eliminate redundant variables. For each term from the full model, the z-score was computed based on its estimation variance. The most insignificant term with z-scores was eliminated, and a new model with fewer covariates was fitted. This procedure was repeated until all variables were significant. The final model includes components listed in Table 1.

Components	**Variables**
Cyclic components	$\sin(\frac{2\pi}{365}day)$, $\sin(\frac{2\pi}{365}day)$
Meteorological components	le, ustar, vpd, ws, precipitation, par
Ecosystem activity	reco, gpp

Table 1: Coefficient estimation for the GLS model with ARMA(1,2) residual structure after backward variable selection.

2.3 Final Model

The final model is of the following form, for $t = 1, 2, \ldots, 5844$,

$$\begin{aligned} y_t &= c + \boldsymbol{\beta}^T \mathbf{X}_t + \epsilon_t \\ \epsilon_t &= \phi_1 \epsilon_{t-1} + \psi_1 \nu_{t-2} + \psi_2 \nu_{t-1} + \nu_t \end{aligned} \tag{1}$$

where y_t is the response, i.e., the NEE of carbon dixocide at time t, $\mathbf{X}_t$ is a vector whose components are the selected variables listed in Table 1, and ν_t's are white noises. ψ_1, ψ_2 are the coefficients of current error depends upon the random shock from the current and previous periods, rather than upon the previous regression error. Moreover, ϕ_1 is the autocorrelation coefficients, c is the intercept, $\boldsymbol{\beta}$ is the coefficient of the corresponding predictor.

2.4 Results

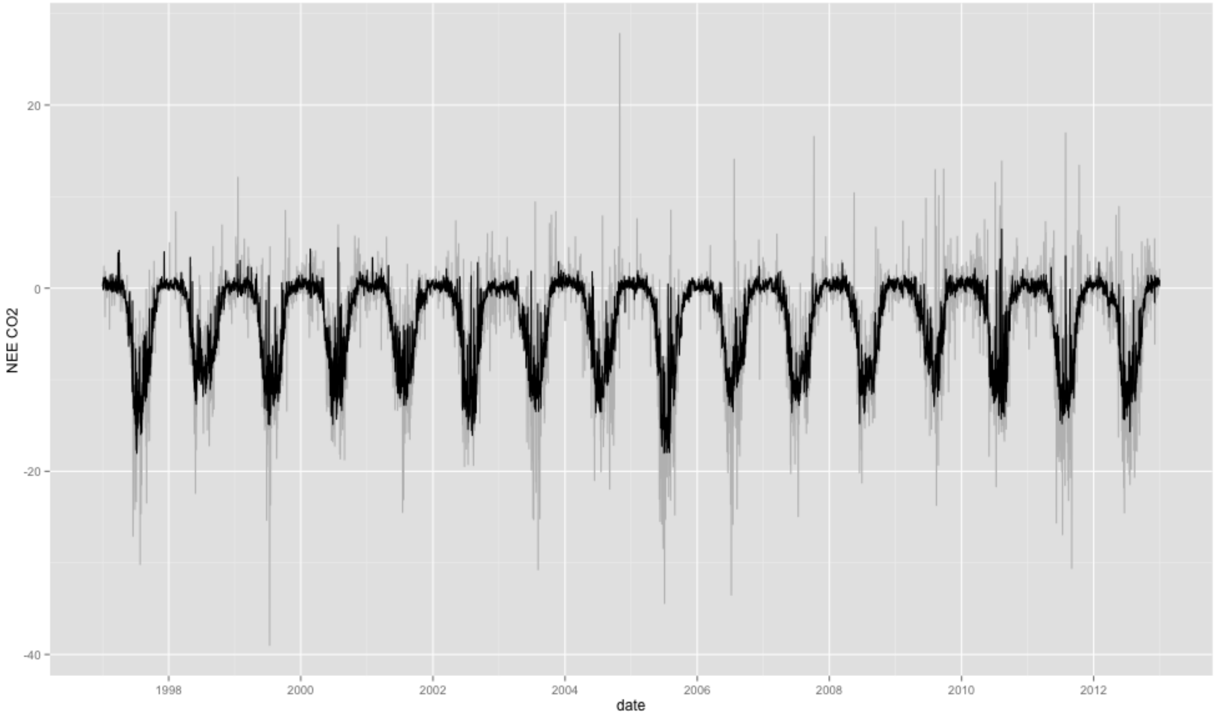

Figure 1: Fitted NEE CO2 from Model (1). The grey line represents the original data and the black line represents the fitted NEE CO2.

Figure (1) shows the fitted NEE from model (1). We can see that the model fits the changing pattern of NEE pretty well. We further investigated the effects of meteorological factors, ecosystem

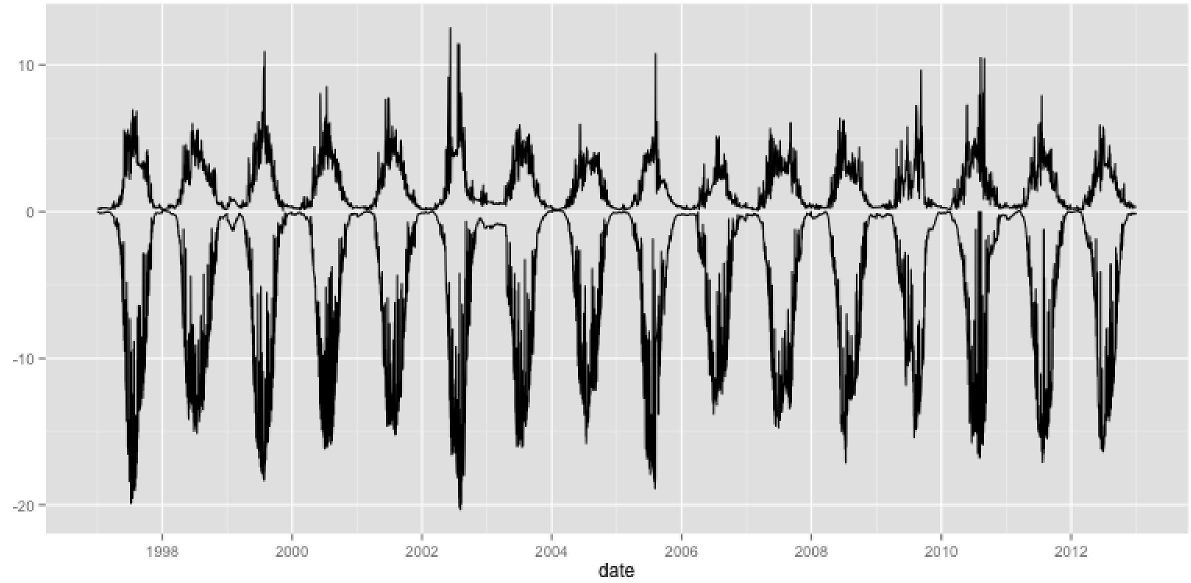

Figure 2: The contribution of ecosystem activities. The top line represents the ecosystem respiration, and the bottom line represents the gross primary product.

activities, and cyclic factors, by multiplying the covariates and the coefficients and add those up. See Figure 6 in Appendix. Figure 2 shows the two major components of ecosystem activities, with reco representing the ecosystem respiration, and gpp indicating the photosynthesis. The former is a measure of CO2 emission, while the latter is a measure of CO2 absorbing. For details of the regression results, see Table 4 in Appendix. Figure 7 and Figure 8 shows the correlation structure and distribution of the residuals. The residuals are centered at zero but also has a large spread, suggesting the existence of extreme values.

From the model fit, we can get following observations.

1. The major contributors to the NEE of CO2 are the ecosystem activities. Both ecosystem respiration and gross primary product reach the peak at month July and August, and drop down near zero in winter months. This is due to the fact that vegetation reaches the maximum growth rate in summer and enters dormancy time during winter.

2. The meteorological factors bring about fluctuations in the NEE of CO2. Specifically, latent heat, velocity of friction, and air temperature are negatively associated with NEE of CO2, while incoming photosynthetic active radiation, water vapor deficit, wind speed are positively associated with NEE of CO2.

3. Interestingly, although the marginal effect of incoming photosynthetic active radiation on

NEE of CO2 is negative (see Figure 9), the coefficient for par in model (1) is found to be positive. The reason may be that the gpp is modeled from par, so after taking account for the effects of photosynthesis, the effects of par only has slight positive effects on the NEE of CO2 (with coefficient estimated to be 0.0008).

4. There is no evidence that NEE of CO2 is increasing or decreasing over time.

3 The Role of Soil Moisture

3.1 Model Choice

Since soil moisture data are only available from July, 2011, a natural way to investigate the effects of soil moisture is to fit a new model using the data from July 2011 to December 2012. Similar to section 2.1, I started with a full OLS linear model and checked the correlation structure of the residuals. Neither PACF nor ACF plot (see Figure 10) suggests dependent residual. So I further build the model using OLS linear regression.

In order to measure the relationship between soil moisture and NEE of CO2, I first fit a simple linear regression model with soil moisture being the only covariate. Then I applied forward selection procedure to investigate the conditional correlation between soil moisture and NEE of CO2.

The final model takes the following form,

$$y_t = \boldsymbol{\alpha}^T \boldsymbol{X}_t + \varepsilon_t, \tag{2}$$

where ε_t are iid normal errors, and $\boldsymbol{X}$ is a vector of covariates listed in Table 2, and $\boldsymbol{\alpha}$ is a vector of coefficients.

Components	**Variables**
Meteorological effects	soil_moist_vwc, h, precipitation, le, h2o
Ecosystem Activities	gpp, reco

Table 2: Variables in model (2)

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3.2 Results

Figure 3 shows the fitted NEE of CO2 from model (2). We can see that model (2) can capture the changing pattern of the NEE CO2 in the investigated time period. For details of the regression

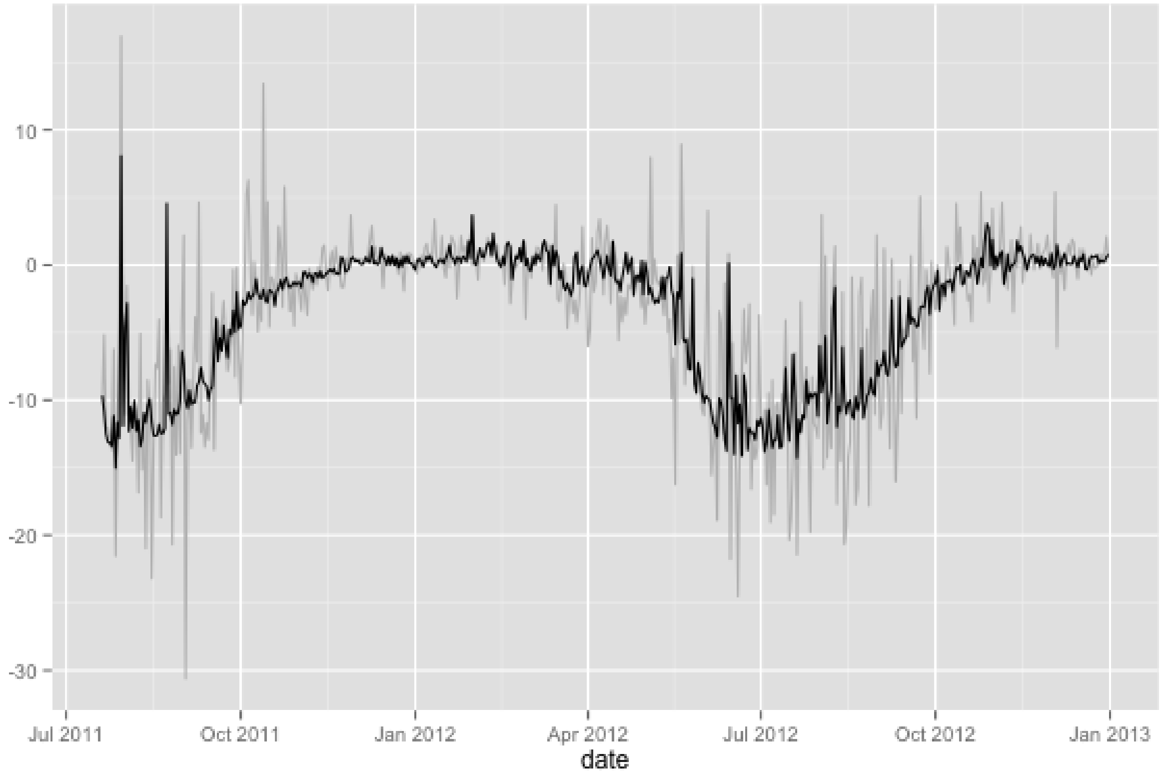

Figure 3: Fitted NEE of CO2 for July 2011 - December 2012. The grey line is the original NEE of CO2

results, see Table 5 in the Appendix. The results shows that there is no evidence that soil moisture is correlated with NEE CO2 with other covariates in presence. On the one hand, soil contribute to the global carbon cycle mainly by soil respiration, whose size might be negligible compared to photosynthesis by vegetation. On the other hand, soil moisture could affect the growth rate of vegetation but such effects might also be very small given more direct measurements such as gross primary product and precipitation.

3.3 Discussion

As is shown in Figure 3, the changing pattern of NEE of CO2 has some noisy part that model (2) fails to capture. Also, with only one-and-a-half-year data available, it is hard to model the cyclic effects or use the previous knowledge about the relationship between NEE of CO2 and other meteorological factors. An alternative way to investigate the effects of soil moisture is to adopt model (1) and see if adding soil moisture improves the model fitting. The results show that after adding soil moisture does not improve the model fitting interns of AIC, suggesting that soil moisture does not further explain the residual of model (1).

4 Conclusions

Based on the analysis in previous sections, we can reach the following conclusions:

1. The net ecosystem exchange of carbon dioxide is associated with three classes of factors: meteorological factors, ecosystem activities, and seasonal factors.
2. The major contributor to the net ecosystem exchange of carbon dioxide is from ecosystem activities. Specifically, ecosystem respiration emit carbon dioxide into the atmosphere, while photosynthesis absorbs carbon dioxide. Both activities reach their peak in summer time and drop down in winter time.
3. Meteorological factors bring about fluctuations to the net ecosystem exchange of carbon dioxide. After accounting for primary gross product, incoming active photosynthetic radiation is positively correlated with net ecosystem exchange.
4. Net ecosystem exchange displays yearly cycle. However, no evidence of increasing or decreasing trend is shown in the data.
5. Soil moisture is not significantly associated with net ecosystem exchange, after accounting for ecosystem respiration, photosynthesis, and other meteorological factors.

This study can be improved in following aspects. First of all, only a small fraction of the data was utilized in the analysis. The major difficulty of employing more data is the noisiness of hourly measured data. Using more data would help us to understand the daily fluctuation of net ecosystem exchange better. Moreover, there are some extreme values in the net ecosystem exchange. This may be caused by the measurements error or theoretical reasons. A simple way to deal with this is to remove or impute the extreme values, but this will cause the loss of information or even over smoothing of the data. An alternative way is to impose more sophisticated time series structure on the residual or on the response and covariates. If the client could provide more information about these extreme values, we may be able to provide a better solution to this problem.

5 Appendix

5.1 Tables

Table 3: Variables and their description.

Variable	Description	Retained in the final model
year	Year (YYYY).	
month	Month (MM).	
day	Day in the year (DDD).	
le	Latent heat flux (W m-2).	✓
h	Sensible heat flux (W m-2).	
ustar	Friction velocity (m s-1).	✓
par	Incoming photosynthetic active radiation (umol m-2 s-1).	✓
tair	Air temperature at 30 m (degrees C).	✓
h2o	Water vapor mixing ratio at 30 m (g kg-1).	
vpd	Vapor pressure deficit at 30m (Pa).	✓
ws	Wind speed at 30m (m s-1).	✓
wdir	Wind direction at 30m (degrees).	
precipitation	Precipitation (mm).	✓
soil_moist_vwc	Near surface soil moisture by volume (percent).	
pressure	Surface air pressure	
nee_co2_filled	Gap filled net ecosystem exchange of CO2 (umol m-2 s-1).	Response
reco	Ecosystem respiration (umol m-2 s-1), derived from nighttime net ecosystem exchange and temperature.	✓
gpp	Gross primary production (umol m-2 s-1), model fit of net ecosystem exchange residual to PAR.	✓
$\sin(\frac{2\pi}{365}\text{day})$	Triangular transformation of day	
$\cos(\frac{2\pi}{365}\text{day})$	Triangular transformation of day	
$\sin(\frac{4\pi}{365}\text{day})$	Triangular transformation of day	✓
$\cos(\frac{4\pi}{365}\text{day})$	Triangular transformation of day	
$\sin(\frac{6\pi}{365}\text{day})$	Triangular transformation of day	✓
$\cos(\frac{6\pi}{365}\text{day})$	Triangular transformation of day	

Table 4: Coefficients estimates and their standard errors (value in the parentheses) for model (1).

Covariate	Coefficient	Covariate	Coefficient	Covariate	Coefficient
intercept	-0.0671 (0.1569)	ustar	-1.7897 (0.2944)	par	0.0008 (0.0001)
le	-0.0081 (0.0008)	tair	-0.0444 (0.0084)	vpd	0.0011 (0.0001)
ws	0.1901 (0.0455)	precipitation	0.6582 (0.0935)	reco	0.5421 (0.0355)
gpp	-0.7907 (0.0178)	sinday6	0.1617 (0.0682)	sinday2	-0.3242 (0.0802)
ar1	0.9829 (0.0071)	ma1	-0.9212 (0.0149)	ma2	-0.0426 (0.0134)

Table 5: Coefficients estimates and their standard errors (value in the parentheses) for model (2).

Covariate	Coefficient	Covariate	Coefficient	Covariate	Coefficient
intercept	-0.0281 (0.5650)	soil_moist_vwc	-0.0700 (1.941)	gpp	-0.8495 (0.0629)
h	0.0082 (0.0019)	precipitation	1.090 (0.2892)	reco	0.7984 (0.1937)
le	-0.0057 (0.0026)	h2o	-0.1623 (0.0810)		

5.2 Figures

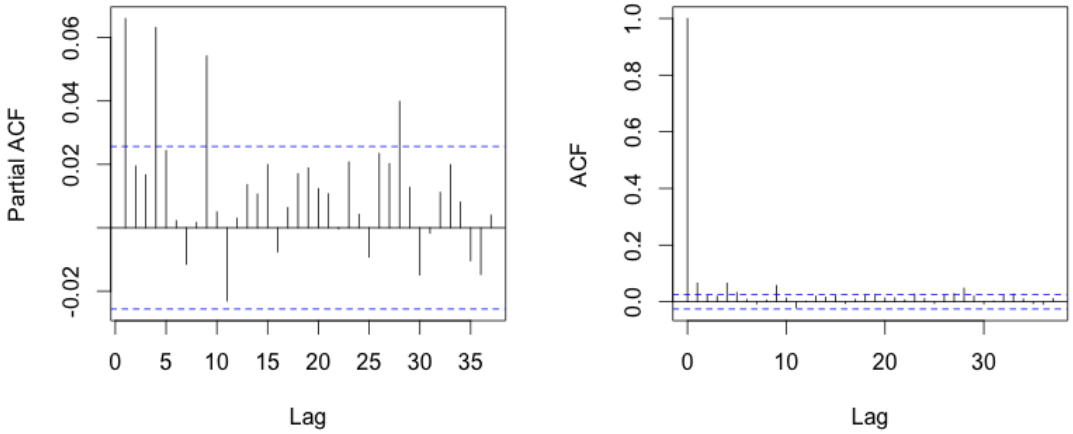

Figure 4: The PACF and ACF plots for OLS residuals.

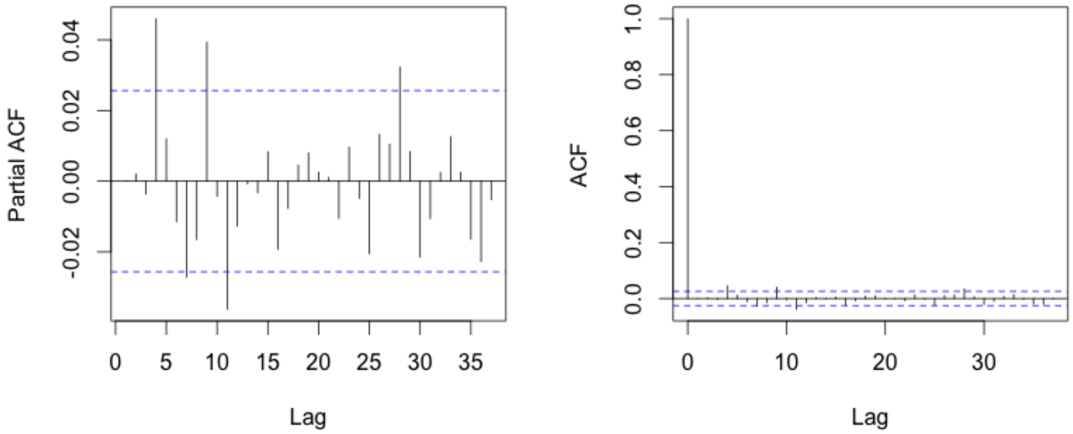

Figure 5: The PACF and ACF plots for ARMA(1, 2) residuals.

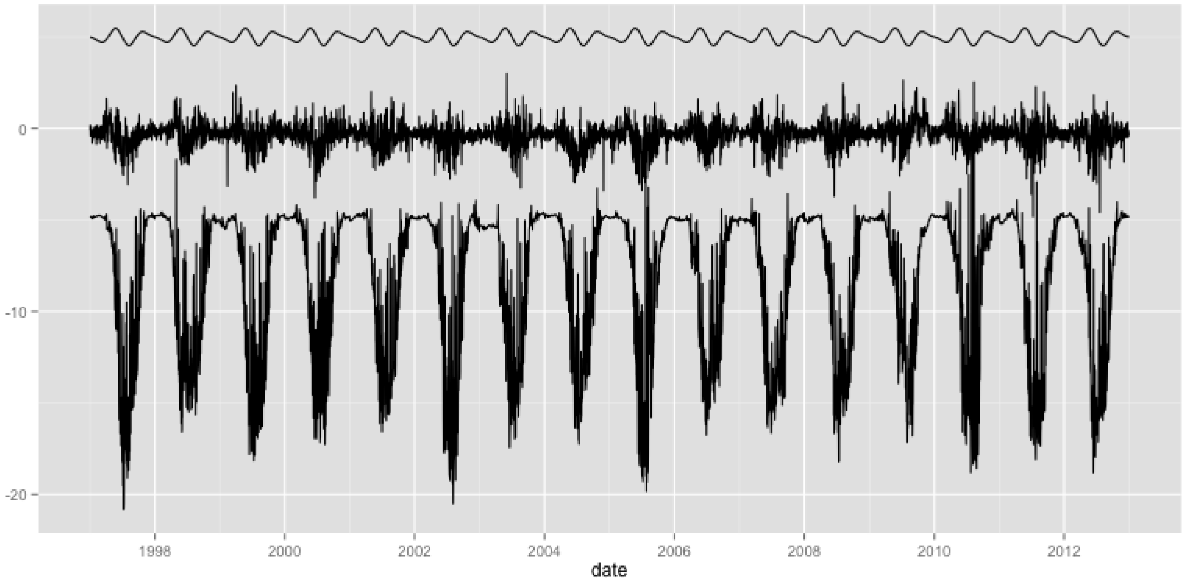

Figure 6: The effects of meteorological factors, ecosystem activities, and cyclic factors. The top line represent the cyclic effect, the middle line represents the meteorological effects and the bottom line represents the ecosystem activities. The top line and the bottom line were added and subtracted 5 from the original scale in order to separate the series.

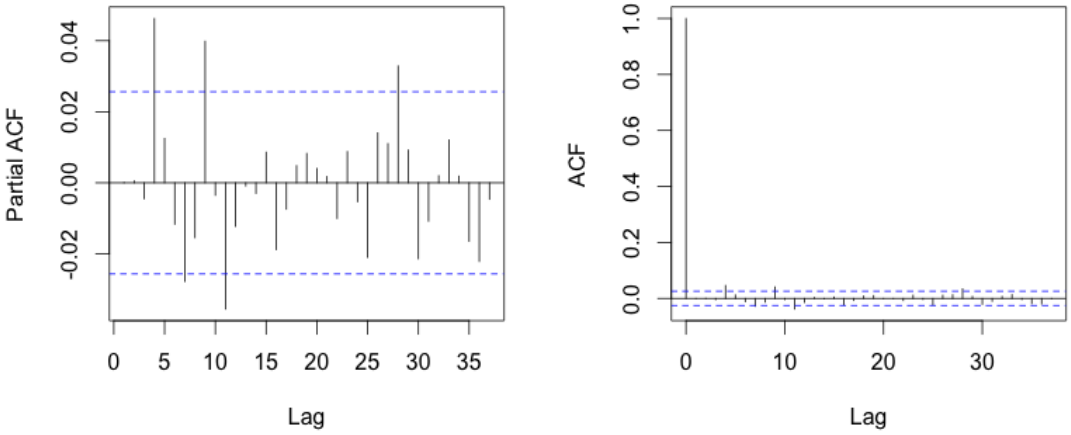

Figure 7: The PACF and ACF plots for model (1) residuals.

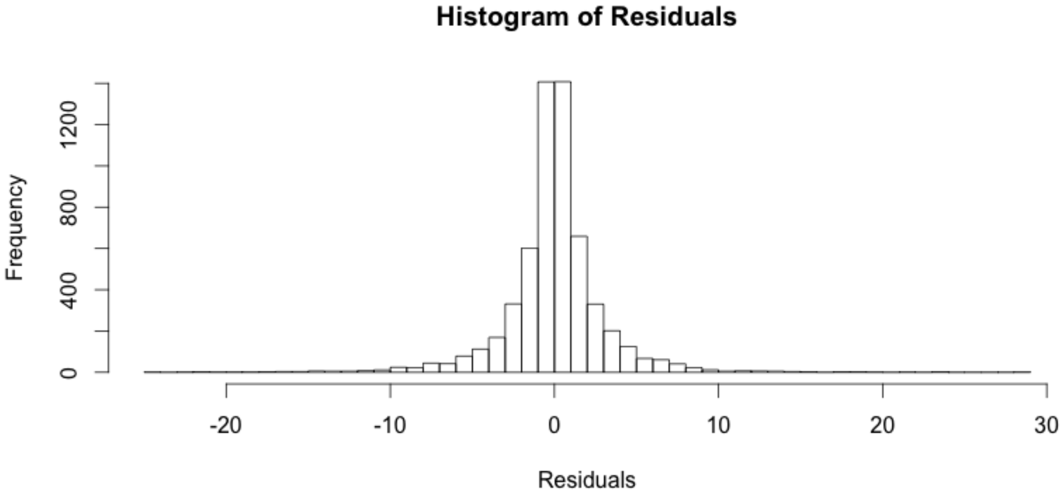

Figure 8: The Histogram for model (1) residuals.

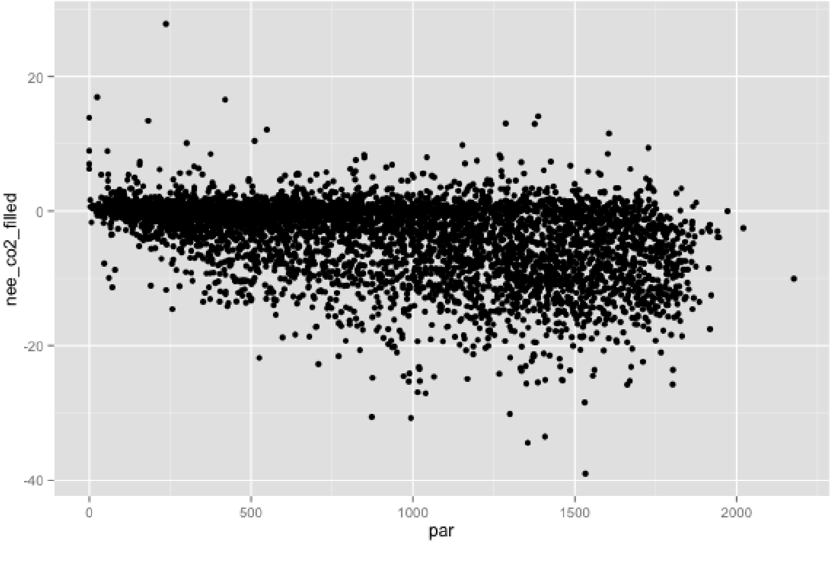

Figure 9: Marginal Effects of PAR.

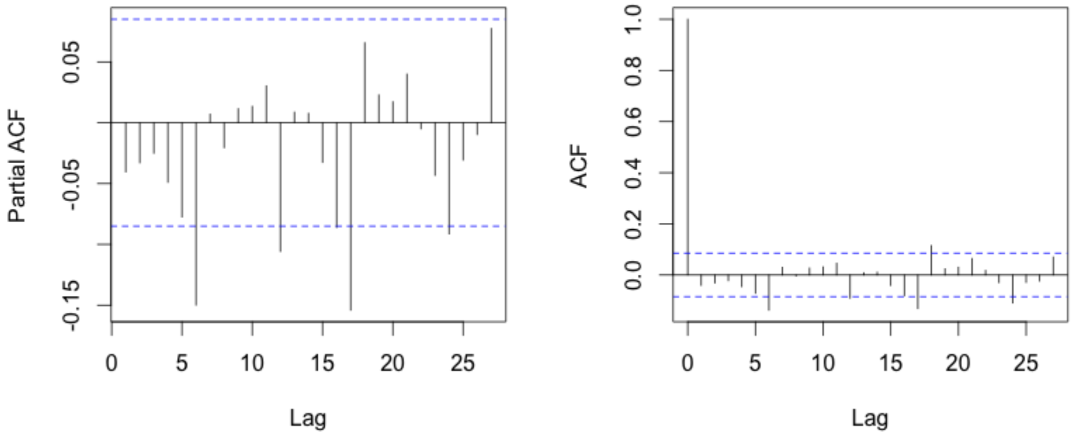

Figure 10: The PACF and ACF plots for residuals using data 2011.7 - 2012.12.

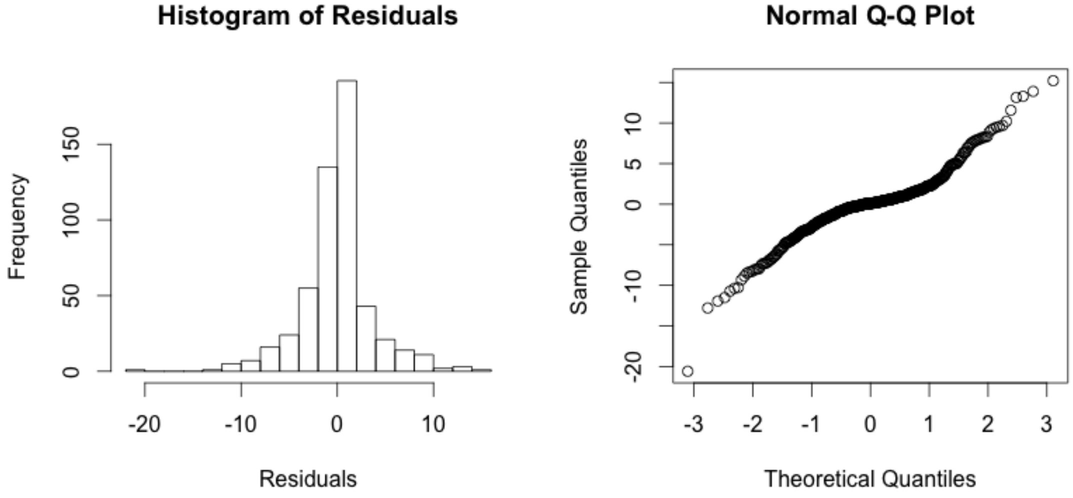

Figure 11: The Histogram and Normal Q-Q plot for model (2).