P1.43 THE CLIMATE AND LONG-TERM WATER BALANCE OF FLUXNET CANADA'S COASTAL DOUGLAS-FIR FOREST

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1. INTRODUCTION

Coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) occupies a large geographic region in the Pacific Northwest from southern California to the mid-coast of British Columbia (Herman 1985). These are some of the most productive forest in North America with a total net primary productivity of up to 8 tC ha^{-1} y^{-1} (Keyes and Grier 1981). On the east coast of Vancouver Island, BC, Canada, Douglas-fir is dominant or co-dominant with western redcedar and western hemlock from sea level to above 1000 m. Over 90% of the stands are second growth Douglas-fir managed on a 50 to 90 year rotation. These sites have a total carbon stock of 300 to 500 tC ha^{-1}, up to half of which is in the trees. About 4 million m^3 of lumber are harvested annually, 16% of the harvest in coastal BC. Productivity of Douglas-fir is strongly influenced by water availability during the late spring and summer (Robertson *et al.* 1990, Carter and Klinka 1990, Gessel *et al.* 1990, Spittlehouse 2003). Water availability is a function of site conditions (slope position, root zone depth, soil texture and stone content), and weather conditions (rainfall, air temperature and humidity and solar radiation).

Flux measurements over a young second growth Douglas-fir stand on Vancouver Island have been made from 1997 to the present (Morgenstern *et al.* 2004) as part of Fluxnet Canada's research network. The annual net ecosystem exchange varied from 2.7 tC ha^{-1} y^{-1} in 1998 (warm and dry) to 4.2 tC ha^{-1} y^{-1} in 2001 (cooler and wetter). There have been substantial inter-annual variation in weather conditions over the last hundred years as well as a trend to warmer temperatures and possibly changes in precipitation (Anon 2002). Consequently, to use the current flux measurements to assess the long-term forest carbon balance we must compare the current weather regime with the long-term record. This paper reports on the first step in this process.

A daily weather record of solar radiation air temperature and precipitation from 1901 to 2003 was created using site data and overlapping records from Environment Canada's weather stations. These data are then used to simulate the April to October summer water balance using measured site characteristics in the model. In these simulations the stand does not age, i.e., it is a simulation of how the current stand might have responded to the range of annual weather conditions over the period of simulation.

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2. METHODS

2.1 *Site Description*

The site, at 300 m above sea level, is 10 km SW of Campbell River on the east coast of Vancouver Island, BC, Canada (49° 52'N, 125° 20'W). This area is in the northern part of the Georgia Basin bounded by the mountains of Vancouver Island to the west and the Coast Mountains to the east. The site is in a dry Coastal Western Hemlock subzone (Meidinger and Pojar 1991) characterised by cool wet winters and warm dry summers. The Douglas-fir were planted in 1949 and are surrounded by similar aged stands. The stands also contain western redcedar (*Thuja plicata,* Donn), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and ferns and salal (*Galtheria shallon*, Pursh) in the understory. In 2002, the trees were 35-m tall, stand density was 1100 stems ha^{-1} and leaf area index was 8.4. The site is on a 5 to 10°NE slope. Soils are gravely sandy loam with a 1-m deep root zone, coarse fragment content of 0.33 and available water storage capacity of 150 mm (Humphreys 2004).

2.2 *Site Flux and Weather Measurements*

Eddy correlation measurements of evaporation and carbon dioxide flux have been made above the canopy from July 1997 to the present (Humphreys *et al.* 2003, Morgenstern *et al.* 2004). Measurements of solar radiation, net radiation, soil heat flux, air temperature and humidity and wind speed were made at 9 m above the canopy. A rain gauge was located just blow the top of the canopy. Rainfall interception by the canopy was measured using five V-shaped throughfall troughs and stemflow collars (Spittlehouse 1998, Humphreys *et al.* 2003). There are no reliable site measurements of the amount of snowfall or its interception.

2.3 *Long-term Weather Data*

Data are from the Meteorological Service of Canada's weather station network in the Georgia Basin. Records were combine to produce one record of daily solar radiation, maximum and minimum air temperature and precipitation from 1901 to 2003. Overlapping records were used to test for homogeneity and develop adjustment factors based on the monthly values (Thom 1966). The reference weather station is Campbell River A (49° 57'N, 125° 16'W, 106 m). Air temperature and precipitation data are available from 1965 to present. This station is about 10 km NE of the forest site. Cumberland (49° 37'N, 125° 02'W, 159 m) has data from 1922 to 1977 including a substantial overlap with Campbell River. It was about 35 km SE of the site. The earliest part of the temperature and precipitation record came from Nanaimo (49° 10'N, 123° 57'W, 31 m) 130 km SE of the site. It has data from 1901 to 1953. Data from other stations in the Georgia Basin (French Creek, Cowichan, Victoria Gonzales, Comox A and Port Hardy A) were used to evaluate homogeneity and fill in data missing from the three primary weather stations.

Solar radiation prior to the site measurements is from Nanaimo and Vancouver (175 km SE of the site). Measured solar radiation was available for Naniamo Departure Bay (49° 13'N, 123° 57'W, 8 m) and Vancouver A (49° 11'N, 123° 10'W, 3 m) from 1959 to 1987, and Vancouver UBC (49° 16'N, 125° 15'W, 93 m) from 1990 to 2000. Missing data were obtained from the daily record of sunshine hours from Vancouver A and Nanaimo A (49° 03'N, 123° 52'W, 39 m) following Hay (1979). Relationships between the ratio of daily actual to potential sunshine hours and actual and clear sky solar radiation were developed for each month. Only monthly sunshine hours were available electronically prior to 1954 for Nanaimo, Nanaimo A and Vancouver A. These data were converted to monthly solar radiation following Hay (1979). Relationships were developed between the difference between maximum and minimum air temperature and the ratio of daily actual and clear sky solar radiation (Bristow and Campbell 1984) and the monthly solar radiation was partitioned between days using of these ratios. A single relationship was used for days with no rain. Days with rain from October to March required a different relationship than those from April to September.

2.3 *Modelling the April to October Water Balance*

In the Georgia Basin, the fall and winter precipitation is large and most of it drains from the root zone. Spring precipitation is usually more than sufficient to ensure that the soil in the root zone is at or above field capacity in late April. Significant soil drying does not usually take place until well into July, depending on root zone depth (Spittlehouse 2003). Consequently, water balance modelling was restricted to the April to October period when there may be water deficits influencing tree growth and carbon sequestration. The same stand conditions are assumed each year, i.e., the stand does not age. The intention is to determine how a 53-year old Douglas-fir stand might respond to the different weather conditions. Also there is no effect of the previous year's conditions on the next year's response.

Root zone water content at the end of day i ($W_{I,}$ mm) is

$$W_i = W_{i-1} + P_i - I_i - Et_i - D_i \qquad [1]$$

where P is rainfall, I is rainfall interception, Et is transpiration and D is drainage from the root zone, for day i. Daily solar radiation, maximum and minimum air temperature and rainfall are used to drive the model. The vegetation and the root zone are each treated as a single layer. The interception and evaporation models use a daily time step, while drainage is calculated every 6 hours if the soil is wet and rainfall high.

Evaporation (E mm d^{-1}) was calculated using daily weather data and the Penman-Monteith equation (Monteith and Unsworth 1990), i.e.,

$$E = (s/[s + \gamma(r_a + r_c)/r_a])[(Rn-G)+(\rho c_p\, D/(s\, r_a)]\ (\rho_w\, 1000/\lambda) \qquad [2]$$

where s, γ and λ are the slope of the saturation vapour pressure curve (kPa $°C^{-1}$), the psychometric constant (kPa $°C^{-1}$) and the latent heat of vaporization (MJ kg^{-1}) at the daily air temperature, Rn is net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), D is the vapour pressure deficit of the air (kPa), ρc_p is the volumetric heat capacity of the air (J m^{-3} K^{-1}), ρ_w is the density of water (kg m^{-3}), r_a is the aerodynamic resistance (s m^{-1}) for the canopy calculated using a constant wind speed above the canopy of 2 m s^{-1} and r_c is the canopy resistance (s m^{-1}). r_c depends on the leaf area index (LAI) of the Douglas fir overstory (DF), the salal understory (SA) and their respective stomatal resistance (r_s, s m^{-1}), i.e., $r_c = 1/[(LAI/r_s)_{DF1} + (LAI/r_s)_{DF2} + (LAI/[r_s+r_b])_{SA}]$. The Douglas-fir canopy is divided into two layers each with LAI 4.2, with the first one assumed to be in full sunlight and the second one at 50% of full sunlight. r_b is the boundary layer resistance (s m^{-1}) of the understory assuming a constant wind speed of 0.2 m s^{-1}, salal leaf diameter of 60 mm and LAI of 0.5. Salal r_b is about 25% of the minimum r_s. r_b for the Douglas-fir is included in the calculation of r_a. r_s is a function of vapour pressure deficit, solar radiation and soil water potential (Tan *et al.* 1978, Spittlehouse and Black 1982). Soil evaporation is small and is neglected. Et equals E when there is no intercepted water on the canopy. Potential evaporation equals the value of Et when the soil is moist enough so that it is not limiting Et.

Daytime values are required for the daily calculations because the stomata are closed at night. A daytime canopy resistance (r_{cd}) function was obtained following Tan and Black (1976) by weighting half-hourly values of r_c by the vpd, i.e., $r_{cd} = \Sigma vpd_i/\Sigma(vpd_i/\ r_{ci})$ and regressing against the daytime average vapour pressure deficit (vpd_d, kPa). Data were adjusted to match the range of r_{cd} reported by Humphreys *et al.* (2003). Formula were determined for three soil water potentials (ψ_s, MPa) i.e.,

$$r_{cd} = r_{cdmin} \quad vpd_d < vpd_{dmin} \quad \psi_s=f \qquad [3a]$$

$$r_{cd} = c + d\, vpd_d + e\, vpd_d^2 \quad vpd_d \geq vpd_{dmin} \quad \psi_s=f \qquad [3b]$$

These values are increased under low light (Tan *et al.* 1978, Spittlehouse and Black 1982). For ψ_s>-0.2 MPa, r_{cdmin}=120 s m^{-1}, vpd_{dmin}=0.8 kPa, and c, d and e are 184, -166 and 102. For ψ_s=-1 MPa, the respective values are 150, 0.7, 301, -363 and 288. At ψ_s=-2.5 MPa the respective values are 580, 0.6, 1153, 1895, 1594. r_{cd} for ψ_s between these ranges was obtained by interpolation.

A relationship for vpd_d was obtained from site data in 2003, i.e., $vpd_d = [0.86(e_sT_x - e_sT_n) -0.11]$, where e_sT_x and e_sT_n are the saturated vapour pressure at the daily maximum and minimum air temperatures (s.e.=0.3,

R^2=0.807, kPa, n=223). In the daily calculation of transpiration, the aerodynamic term in equation [2] was multiplied by the fraction of the day as daylight hours.

Daily interception loss (I_i, mm) was calculated with

$$I_i = 12\, P_i / (P_i + 20) \qquad [4]$$

This function was derived from individual storms rather than daily totals. However, most storms during the April to October period last for less than 24 hours. Intercepted water is evaporated assuming r_c=0 and at 70% of the daily rate to allowing for the canopy being partially wet during drying. If all of the intercepted water does not evaporate during the day, that remaining reduces interception the next day if there is rain and evaporates on that day. Evaporation of interception suppresses transpiration.

Daily net radiation (Rn, MJ m^{-2} d^{-1}) is calculated with the following equations

$$Rn = S_g - a_f S_g + L_d - L_u \qquad [5a]$$

$$L_d = \varepsilon_s \sigma T^4 \qquad [5b]$$

$$L_u = 0.98 \sigma T_a^4 \qquad [5c]$$

$$\varepsilon_s = (1 - 0.84n)\varepsilon_{clear} + 0.84n \qquad [5d]$$

$$n = (1 - S_g/S_{gclear}) \qquad [5e]$$

$$\varepsilon_{clear} = (0.53 + 0.206 e_a^{0.5}) \qquad [5f]$$

$$S_{gclear} = 18.9 + 12.7(\sin[0.0172(DoY - 81)]) \qquad [5g]$$

where S_g is the solar radiation (MJ m^{-2} d^{-1}), a_f is the albedo (=0.09, Humphreys 2004), L_d is the downward longwave radiation (MJ m^{-2} d^{-1}), L_u is the upward longwave radiation (MJ m^{-2} d^{-1}) at the daily mean air temperature (T_a, K), ε_s is the sky emissivity, σ is the Stefan-Boltzman constant (4.9×10^{-9} MJ m^{-2} d^{-1} K^{-1}), T is the mean daily air temperature (K), n is the fraction of cloud cover, ε_{clear} is the clear-sky emissivity, S_{gclear} is the maximum clear-sky radiation at the ground for the day, DoY is the day of the year, the sine is in radians and e_a is the mean daily vapour pressure assumed equal to the saturated vapour pressure at the minimum air temperature. A comparison of measured (Rn_M) and modelled (Rn_S) net radiation for 2003 gave Rn_M=1.01Rn_S + 0.09, se=0.74 MJ m^{-2} d^{-1}, R^2=0.982, n=214. Rn is increased by 3% for daylight hours in the calculation of Et. The soil heat flux = 0.03 Rn-0.09 MJ m^{-2} d^{-1}. Canopy heat storage is neglected.

The soil water potential (ψ_s, MPa) and drainage (D, mm d^{-1}) functions are based on those of Spittlehouse and Black (1981) for similar soil 8 km SE of the site. The functions were adjusted for the bulk density and coarse fragment content of the site, i.e.,

$$\psi_s = 0.001\, (\theta/0.33)^{-5.9} \qquad [6a]$$

$$D = 100\, (\theta/0.33)^{14.8} \qquad [6b]$$

where $\theta = W/\zeta$ is the water content of the root zone and ζ is the depth of the root zone (mm).

3. RESULTS

3.1 *Weather Record*

Data for Campbell River A were well correlated with the site and with Cumberland (Table 1). Precipitation was not as well correlated as temperature between Nanaimo and Cumberland. Solar radiation correlation was best in the summer months and improved with averaging over two or three days. Correlation was better in summer than winter (R^2=0.77 and 0.62 respectively) for daily and monthly relationships between solar radiation and sunshine hours. The annual temperature, precipitation and solar radiation data for 1901 to 2003 for the forest site are presented in Figure 1. As expected, the 103 years have a large inter-annual variation. The mean annual temperature for the forest site is 7.8°C and average precipitation is 1483 mm. The extreme maximum temperature was 39°C and extreme minimum –21.5°C. Annual and summer patterns are similar. The 1990-2003 period has minimum temperatures averaging 1.2°C warmer than the previous ninety years. The maximum temperatures average 0.2°C warmer. This is consistent with trends across much of Canada. The variation in annual and seasonal precipitation from 1997-2003 is similar to the rest of the record.

Solar radiation has a peak in the mid 50's to mid 60's. It spans a period of sunshine and solar measurements and is not an artifact of changes in measurement technique. It corresponds to a period with warmer minimum temperatures. Annual and summer patterns are similar.

Table 1. Relationships between the main weather stations and between Campbell River A and the forest site used to develop the long-term weather record. Tmax and Tmin are the maximum and minimum temperatures (°C), PPT is precipitation (mm) and Solar is solar radiation (MJ m^{-2} d^{-1}). Monthly averages or totals were used for all except daily totals for solar.

Stations		Slope	Intc.	R^2	n
Campbell A to Site	Tmax	0.97	-2.22	0.994	78
	Tmin	0.99	-1.29	0.958	78
	PPT	1.0	0	0.960	50
Cumberland to Campbell A	Tmax	0.98	0.15	0.980	118
	Tmin	1.02	-0.07	0.973	118
	PPT	1	0	0.900	122
Nanaimo to Cumberland	Tmax	1.08	-1.52	0.971	288
	Tmin	0.92	-2.56	0.966	288
	PPT	1.75	0	0.824	288
Vancouver UBC to site	Solar	1.0	0	0.810	323

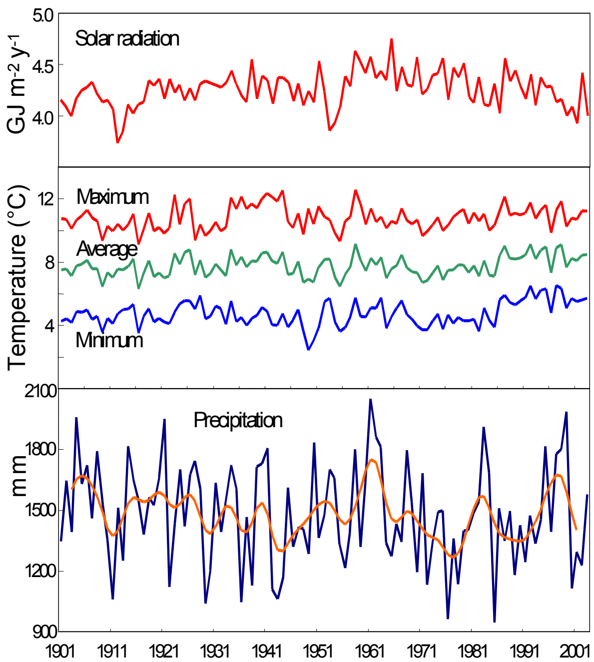

Figure 1. Annual solar radiation, air temperature and precipitation for the forest site from 1901 to 2003. The smooth line in the precipitation panel is a Gaussian weighted 10-year moving average.

3.2 Water Balance Modelling

Site radiation, temperature and humidity data were used to simulate the water balance from 1997-2003. Humphreys et al. (2003) measured 318 and 319 mm of evaporation during the summers of 1998 and 1999. The modelled values are 341 and 312 mm. Modelled values simulated with adjusted Campbell River A data and simulated net radiation are 345 and 353 mm. The increase in 1999 is due to higher simulated transpiration during the June to August period. Over the seven years, simulated April to October transpiration from measured and modelled site data agreed quite well, i.e., measured = 1.04modelled - 26, s.e.=13 mm, R^2=0.781, n=7.

Figure 2 shows the simulated April to October transpiration and evaporation of intercepted water. The 1997-2003 period has slightly lower transpiration rates than earlier periods. Water deficits also tend to be lower during this period (Figure 3). Water deficit is the difference between transpiration calculated assuming there are no soil water restrictions and actual transpiration. The late 1930's to the mid 1960's have the highest deficits, corresponding to years with low summer rainfall and high air temperature (Figure 1).

Total evaporation during April to October ranged from 320 mm to 490 mm with a mean of 410 mm. Transpiration ranged from 240 to 385 mm with a mean of 302 mm. The potential transpiration (no soil water limitation) ranged from 255 to 450 mm. Water deficits usually occur in late July, August and September. Deficits are 50 mm or less 75% of the time. Rainfall interception ranged from 66 to 190 mm with a mean of 109 mm. Consequently, 30 to 40% of the summer rainfall never reaches the ground.

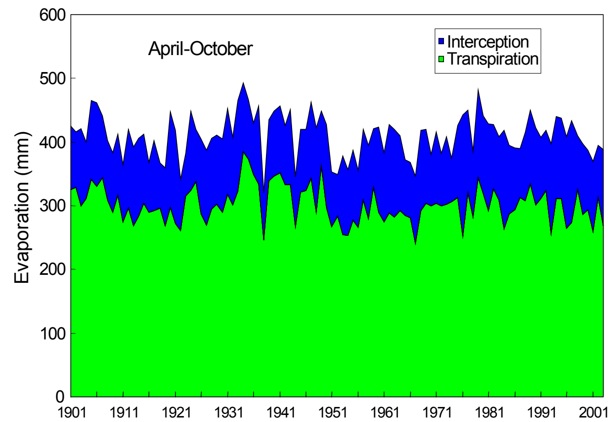

Figure 2. Simulated total transpiration and evaporation of interception for the April to October period 1901 to 2003.

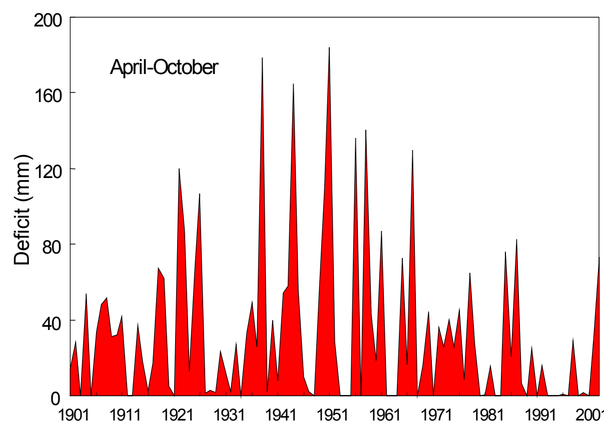

Figure 3. Simulated April to October water deficit (potential – actual transpiration) for 1901-2003.

4. DISCUSSION

Agreement between measured and modelled data during 1997-2003 is good, giving confidence that the modelling approach can be used to estimate past evaporation rates. Spittlehouse (2003) obtained good agreement between evaporation calculated with daily daytime data and half-hourly data. Evaporation is mainly driven by the aerodynamic term in equation 2. Thus any errors in the solar radiation record and in the simulated net radiation will not have a large influence on evaporation. The vpd is the most important variable driving transpiration and it is also used to predict canopy resistance. The uncertainty in the estimate of daytime vpd is 0.3 kPa, 10 to 15% of the vpd under high evaporation rates. Increasing vpd increase r_c. The canopy resistance function has transpiration peaking at a vpd of about 2 kPa and remaining constant or slightly decreasing as the vpd further increases (Tan *et al.*

1978). This feed back reduces the effect of the uncertainty in vpd on the simulated evaporation.

Even though the site has a deep root zone, the low summer rainfall means that there are occasionally significant water deficits. Spittlehouse (2003) shows that reducing the amount of available water during the May through July significantly decreases tree growth. The flux measurement period of 1997 to 2003 appears to have been less severe for water limitations than earlier in the 1900s. 1998 and 2002 had deficits starting in a late August, while 2003's deficit started at the beginning of August. These deficits were in response to low May though August rainfall. Over the 103-year simulation, 12% of the years had significant deficits from July through September and 22% in August and September. This could mean that on average the measurement years over-estimate carbon sequestration for such stands. However, the last decade had an average temperature 0.7°C warmer than 1901-89. The monthly respiration and temperature function from Morgenstern *et al.* (2004) gives about 10% more respiration for this period compared to the previous ninety years. The increase in respiration would reduce net ecosystem exchange.

5. CONCLUSIONS

There was a 10-to-20% inter-annual variability in the April to October evaporation. This was driven mainly by the variation in the amount of rainfall. The carbon dioxide flux measurements have been made during a period with less water restrictions to transpiration than in the past. However, the minimum air temperatures have been greater and this could cause an increase in respiration offsetting potential increases in gross photosynthesis. Extrapolation of the measurements of net ecosystem exchange to the longer term needs to be done with care.

6. ACKNOWLEDGMENTS

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