Orographic Precipitation (OP)
and
Isotope Fractionation

1. Fractionation Observations
2. Estimating the Drying Ratio
3. Drying Ratio Model
4. Sensitivity to climate change

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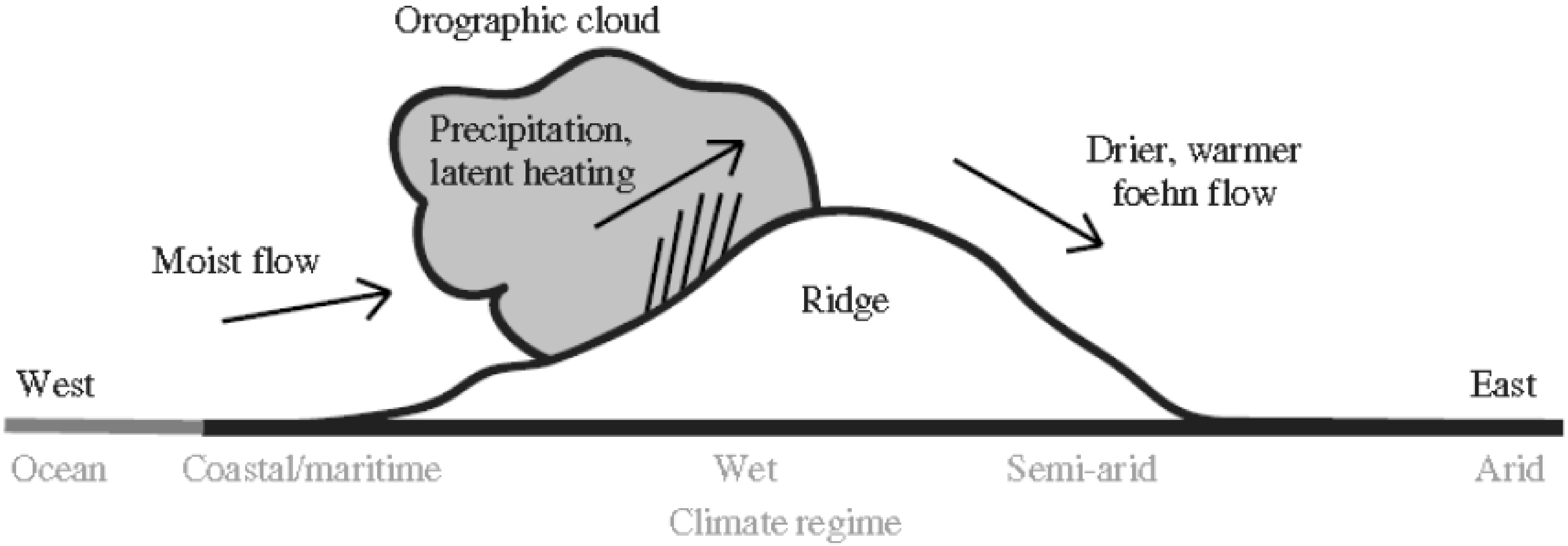
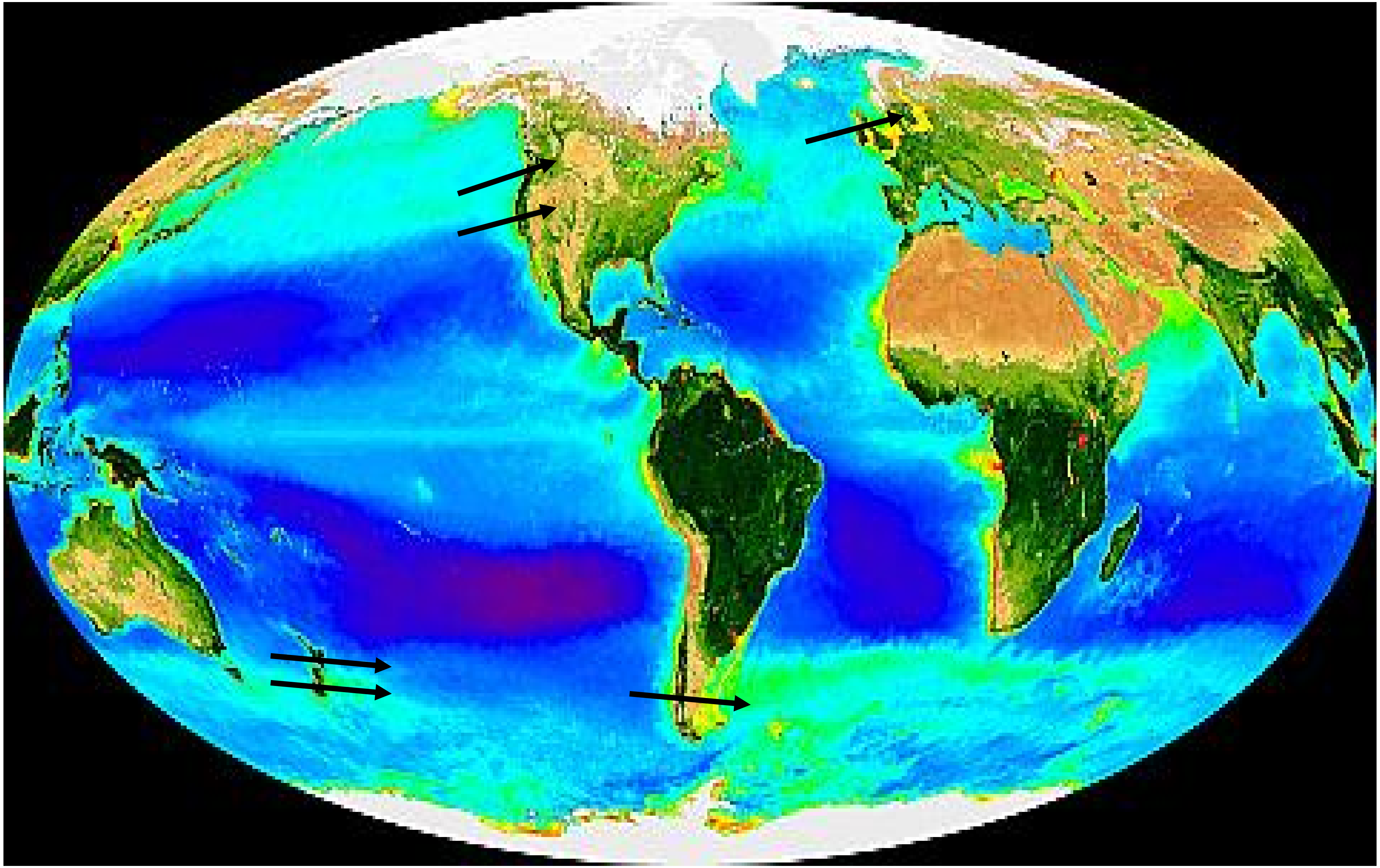


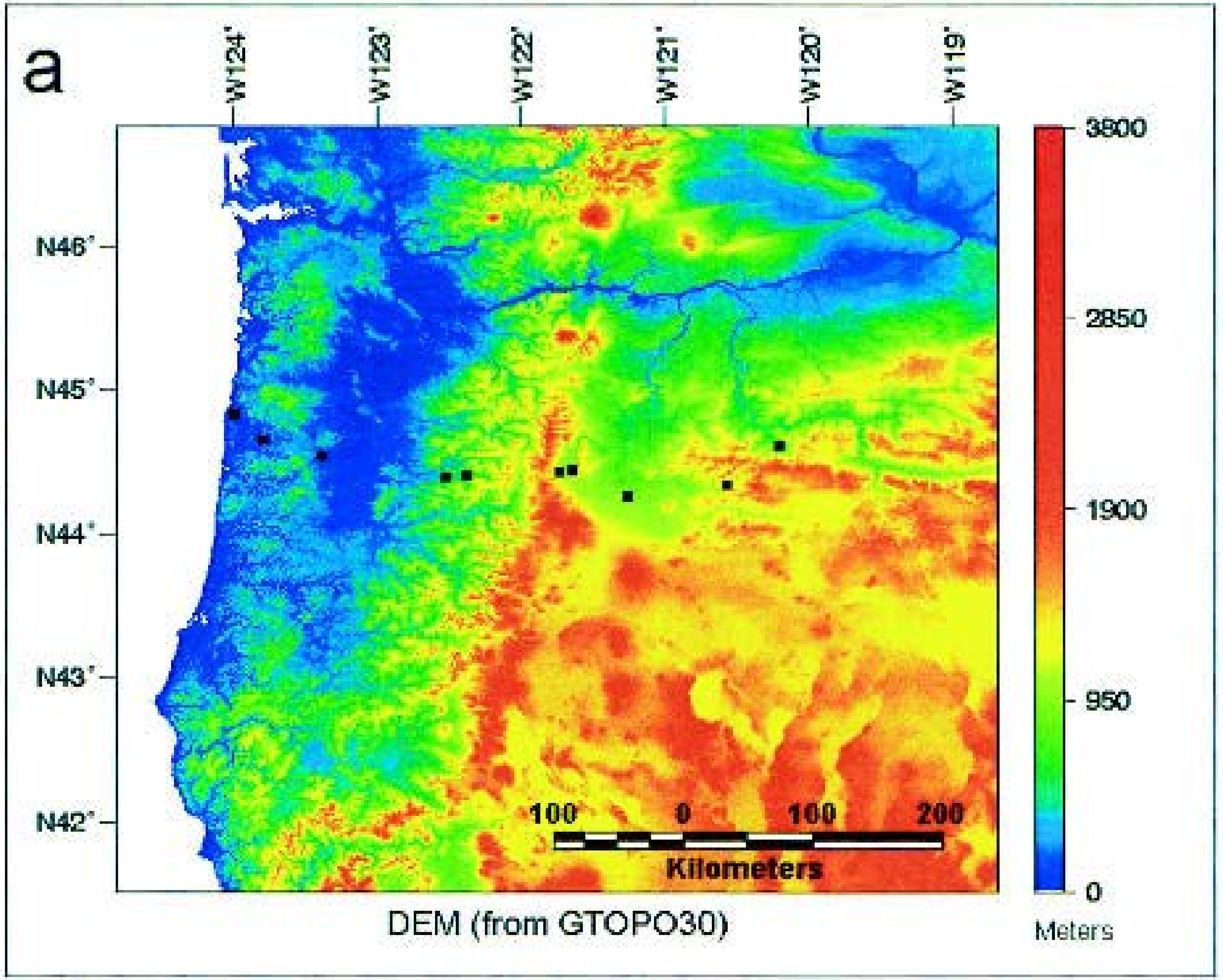
Schematic diagram of orographic precipitation. Airflow is from left to right. Moist ascent is followed by dry descent (Kirshbaum and Smith 2008)

Orographic Precipitation and Isotope Fractionation

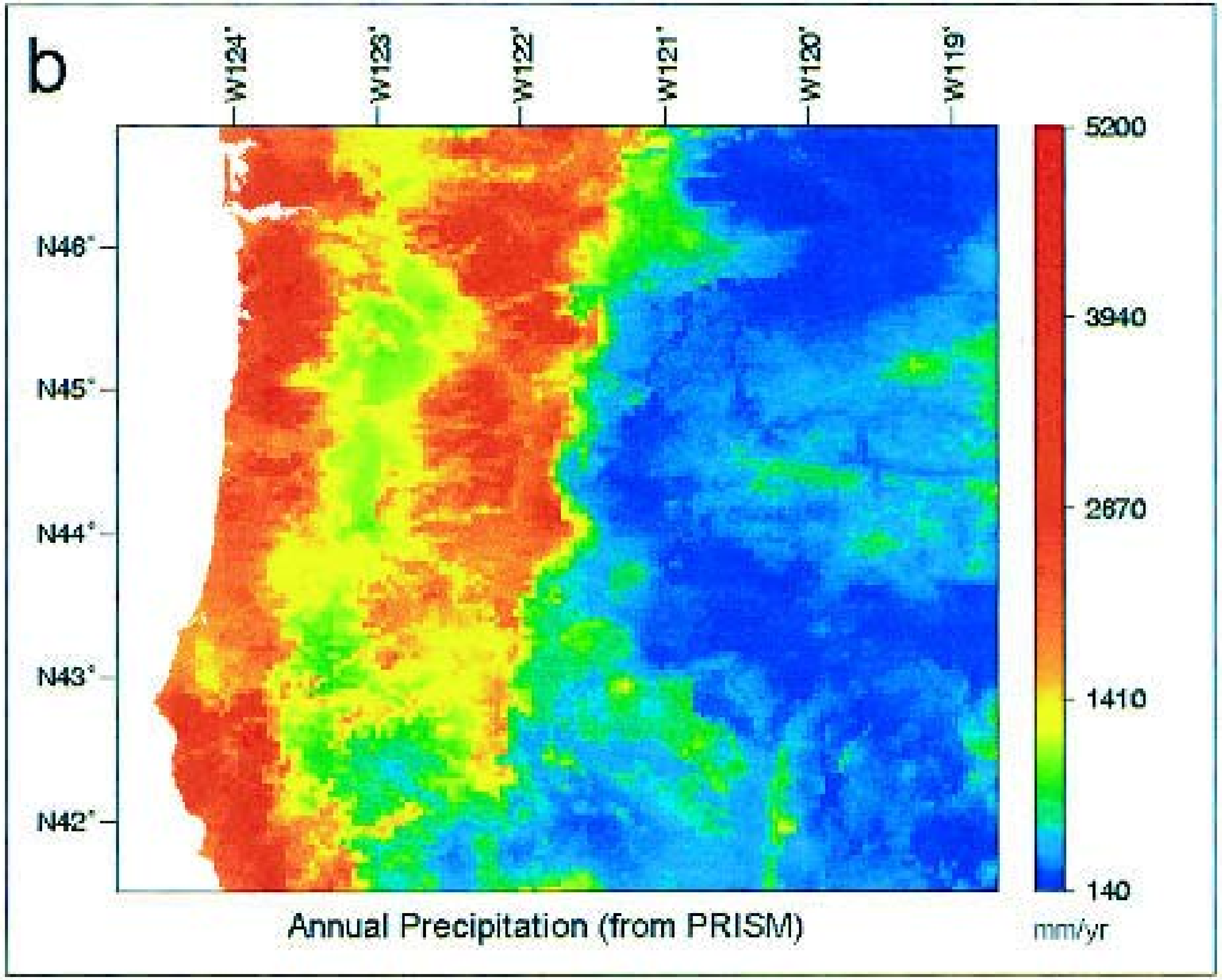


Cascades in Oregon

Terrain(m) and Stream Sampling Sites



Annual Rainfall (mm)



Cascades in Oregon

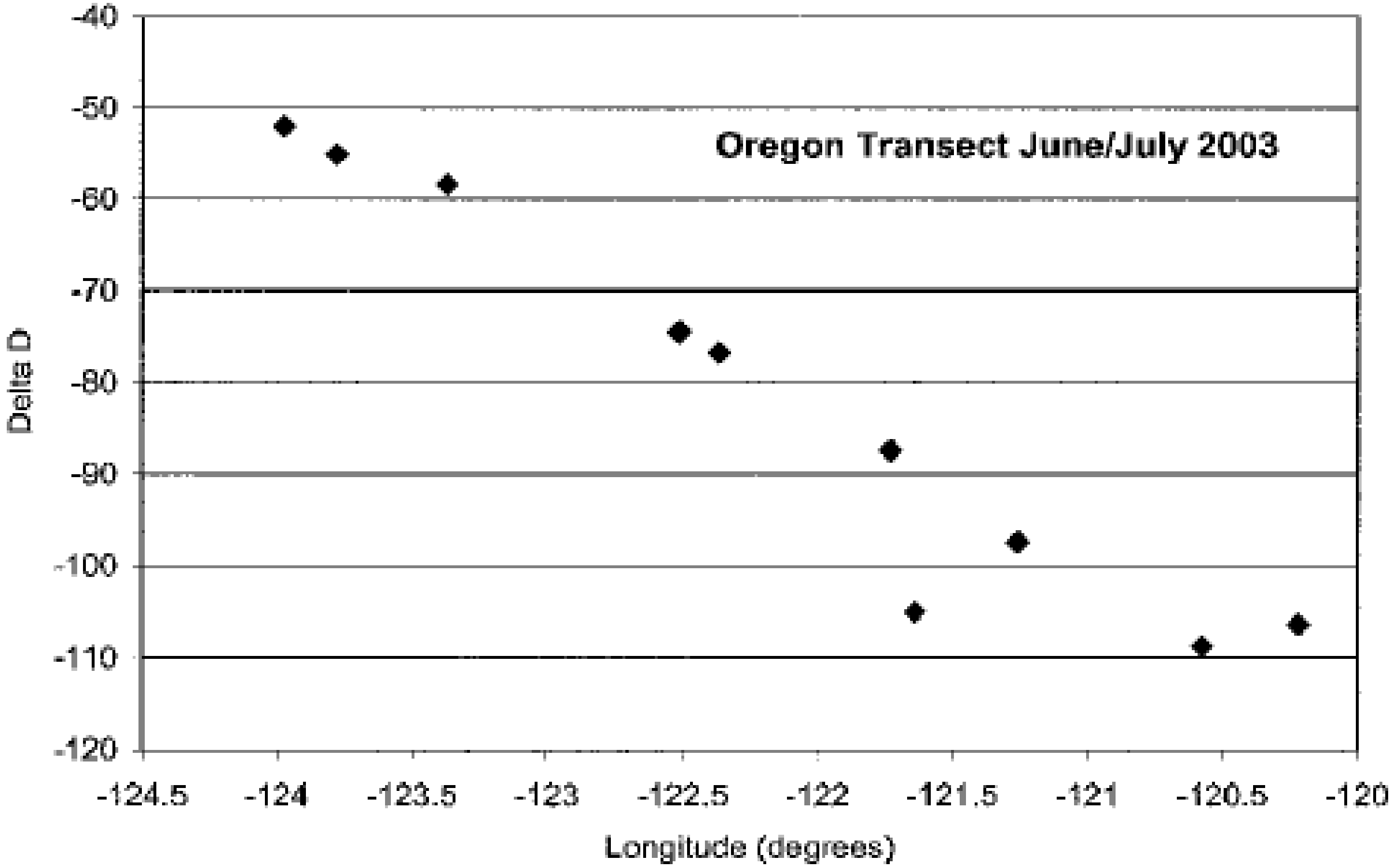
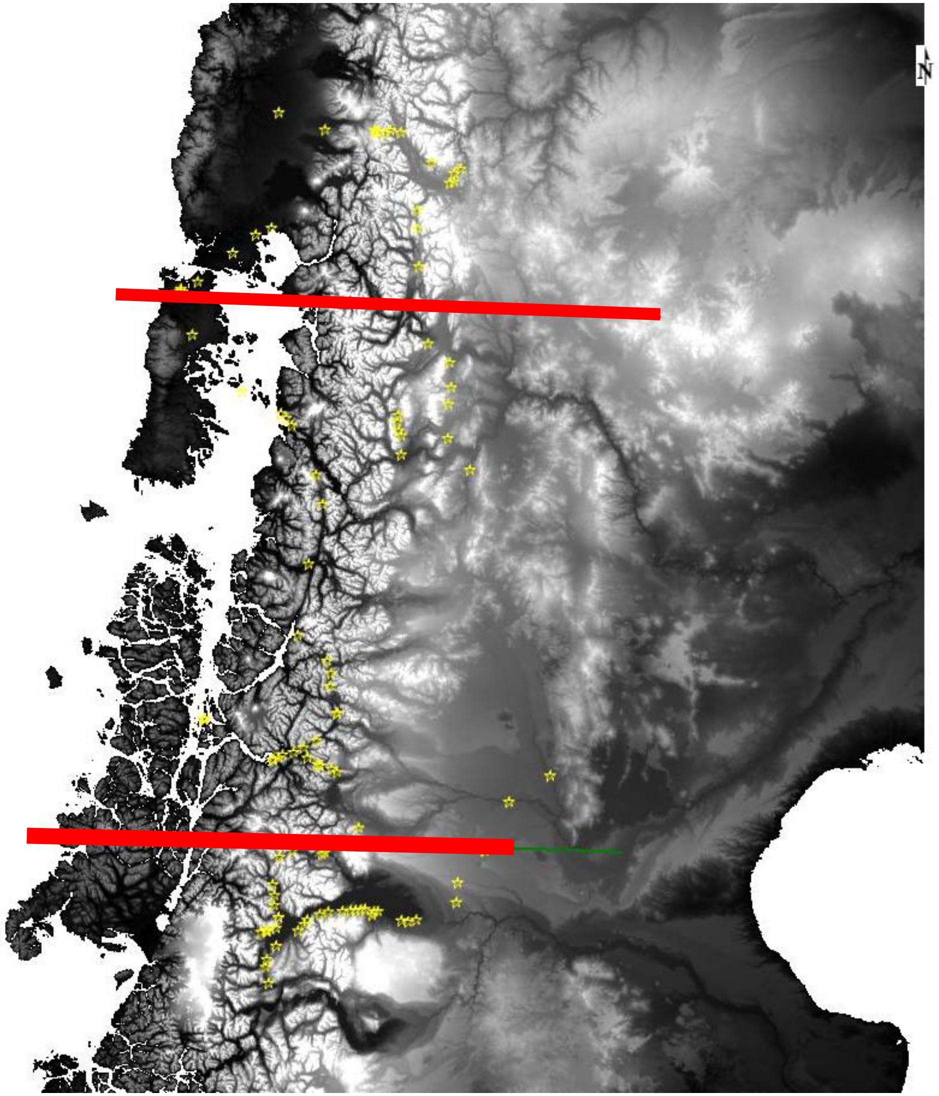
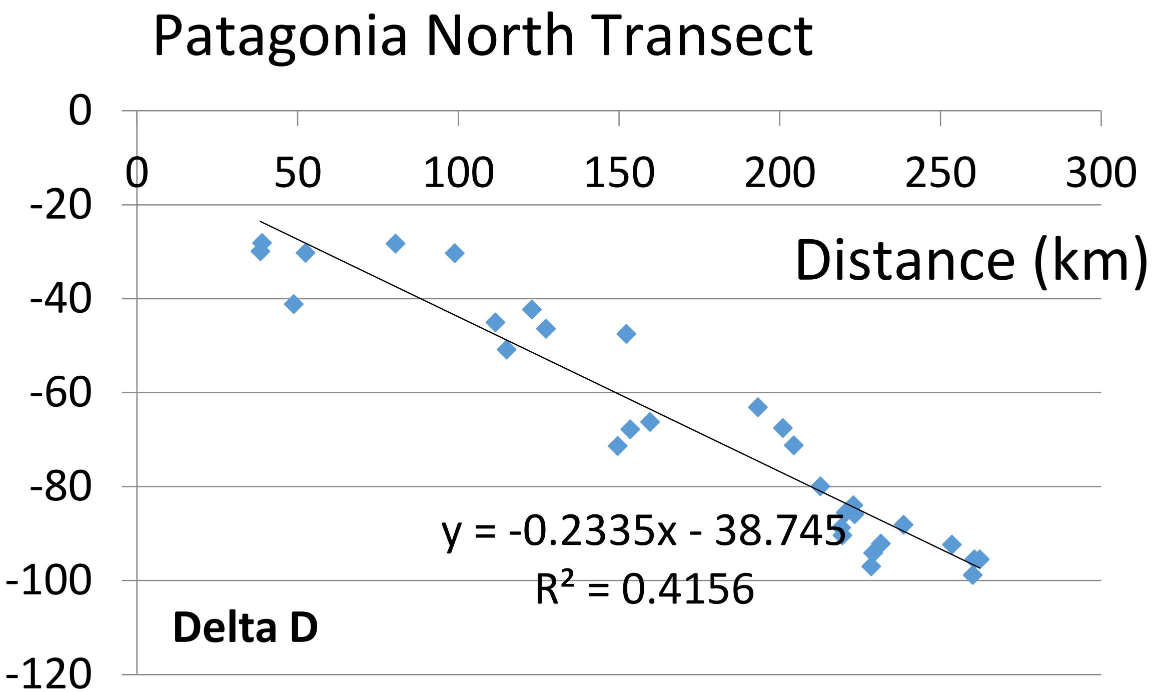


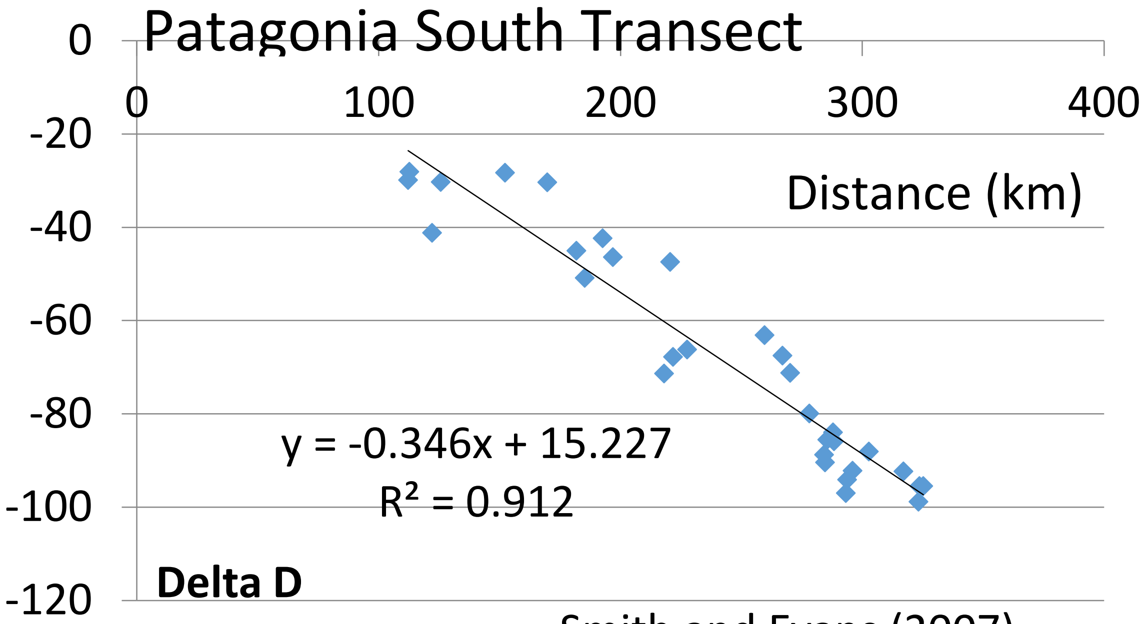
FIG. 8. Deuterium isotope ratios in stream water samples collected in Jun–Jul 2003. Sample locations are shown in Fig. 4a.

Smith et al. 2005

Southern Andes







Smith and Evans (2007)

Southern Andes

D vs. 18O

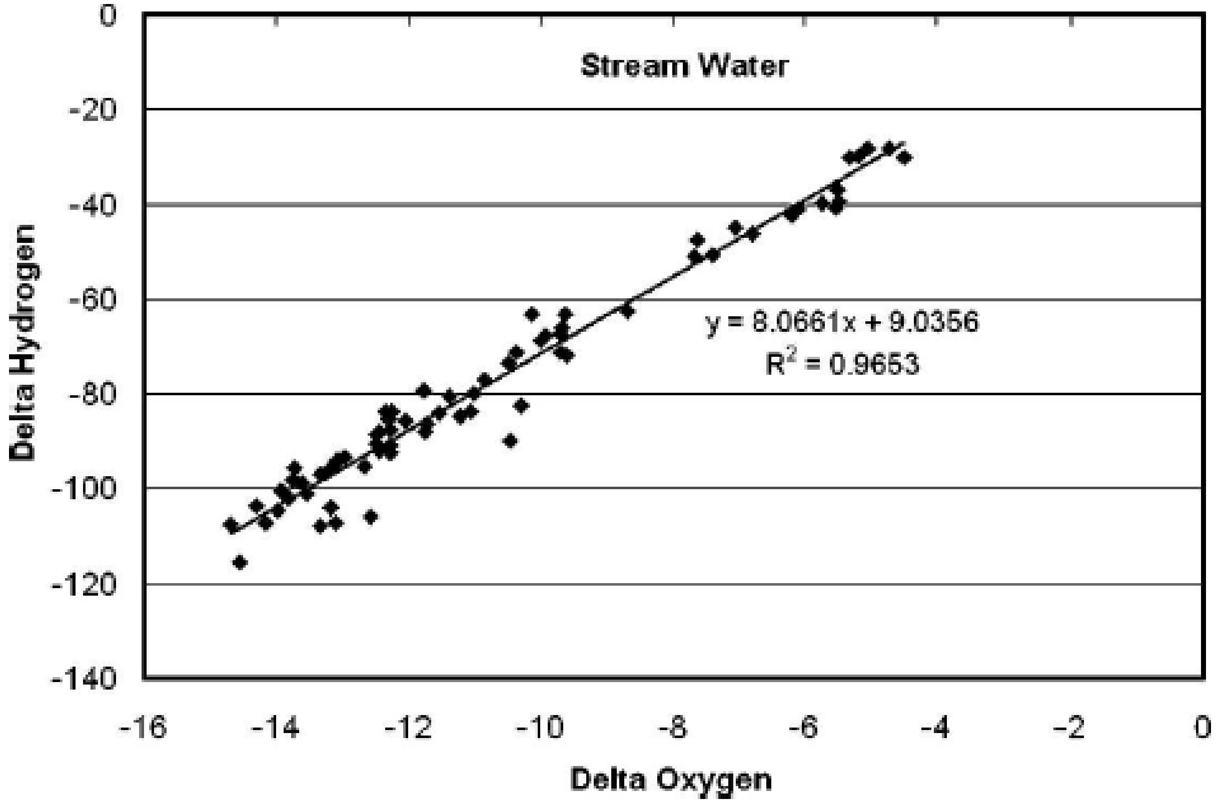


FIG. 5. Oxygen vs hydrogen isotope data for Patagonia streamwater samples. Note that the trend-line slope (8.0661) and intercept (9.0356) approximate the standard meteoric water line (slope = 8 and intercept = 10).

Stream vs. Stem Water

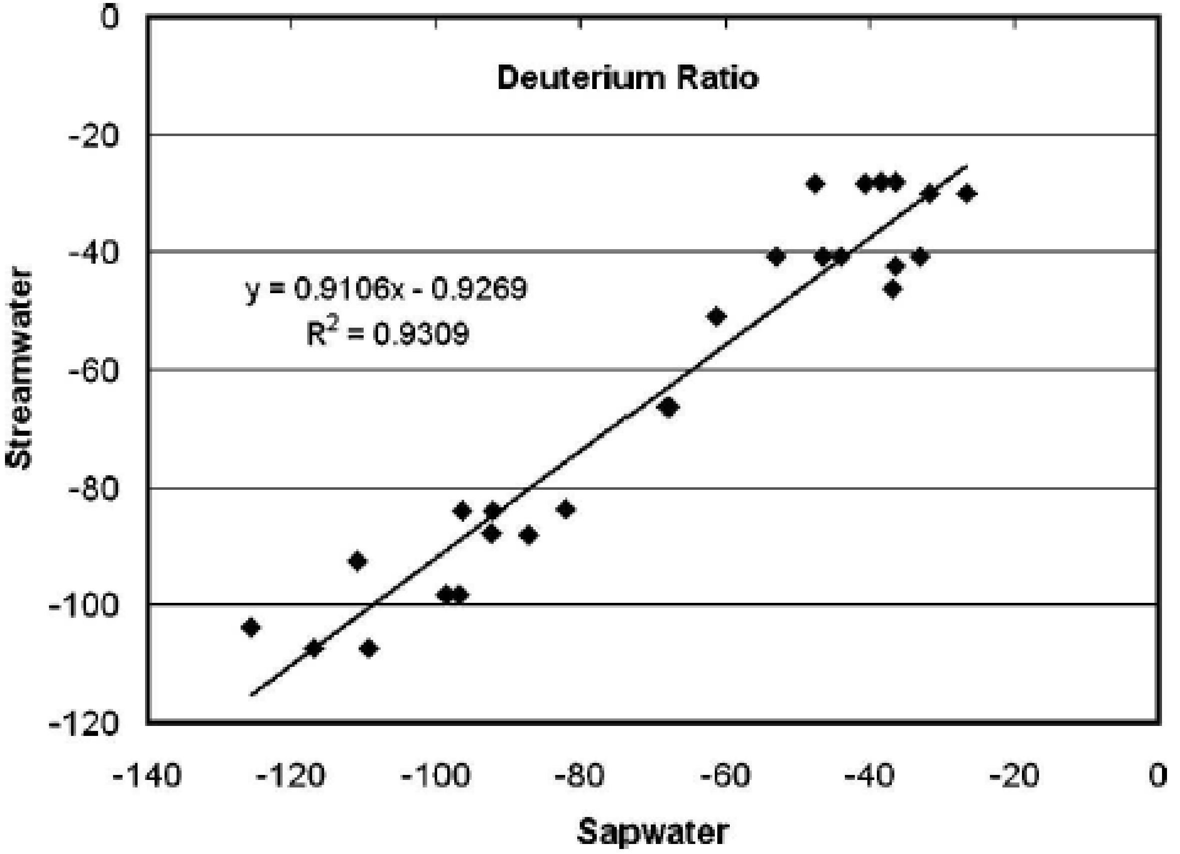
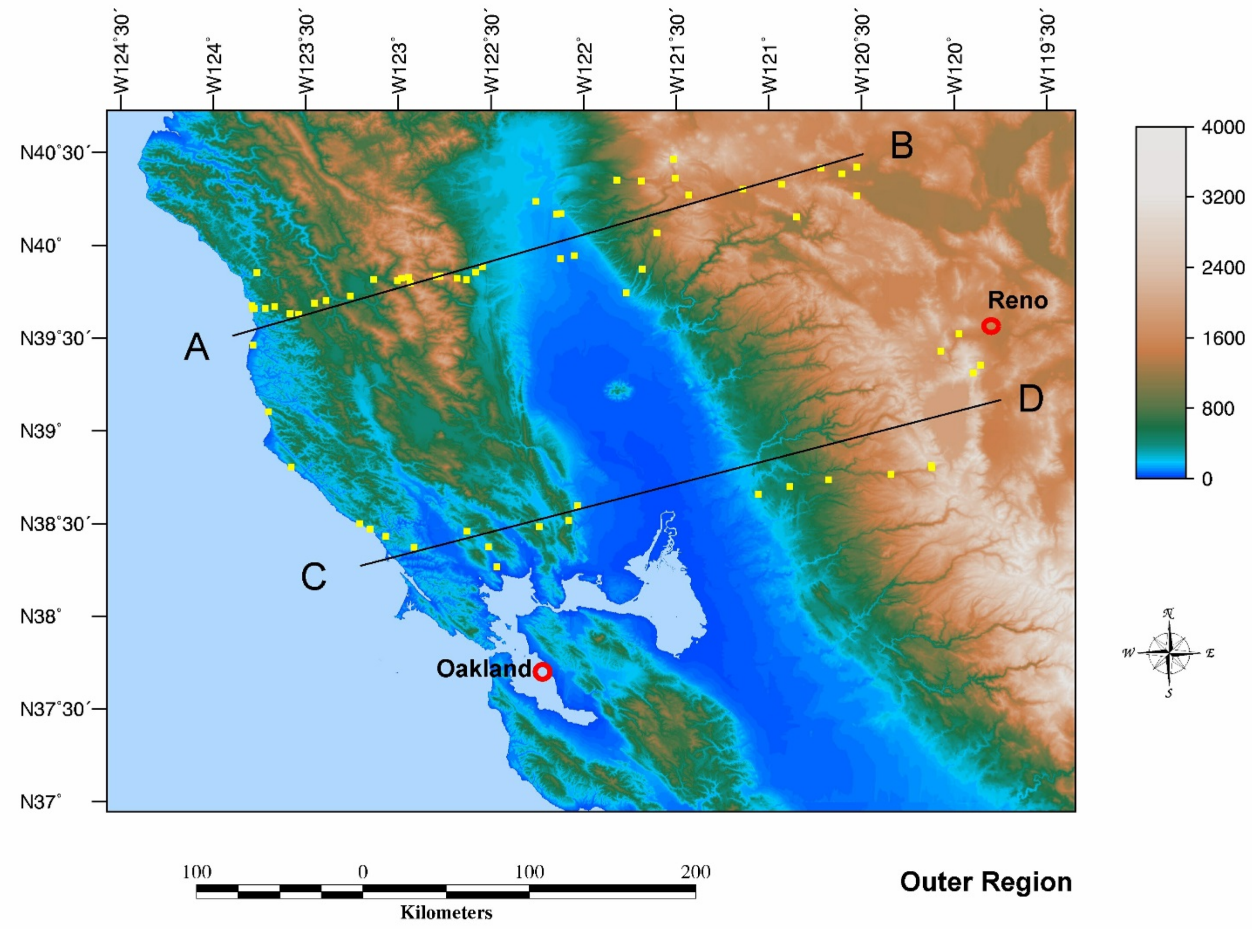
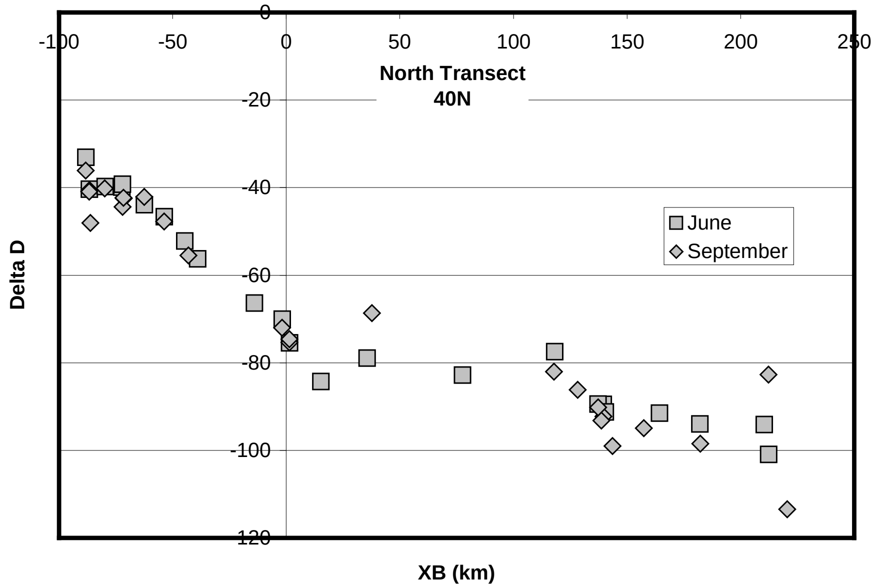


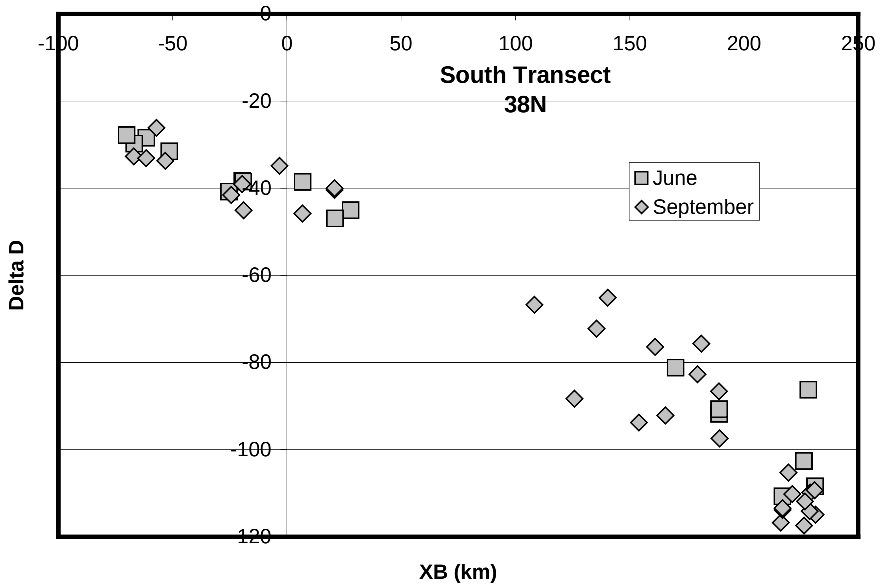
FIG. 12. Deuterium from sapwater vs streamwater from sites where both were collected across the southern Andes. A trend line is shown with slope 0.9106 and intercept 0.9269.

Smith and Evans (2007)

California Sierra Nevada Range (June & September)



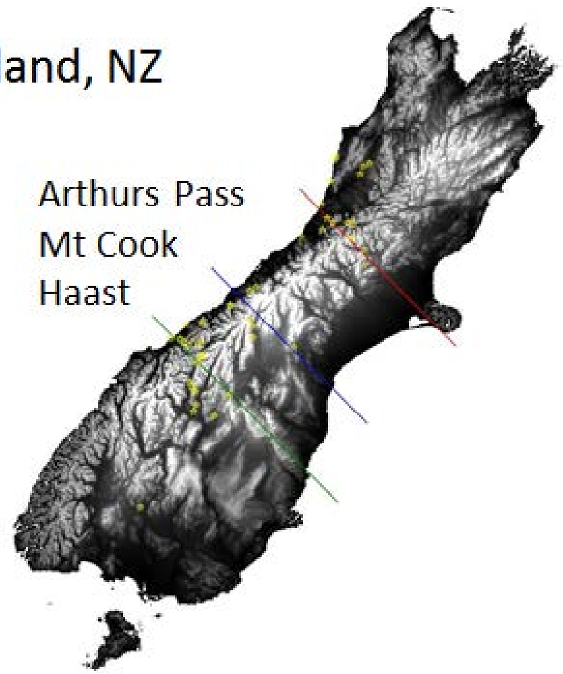


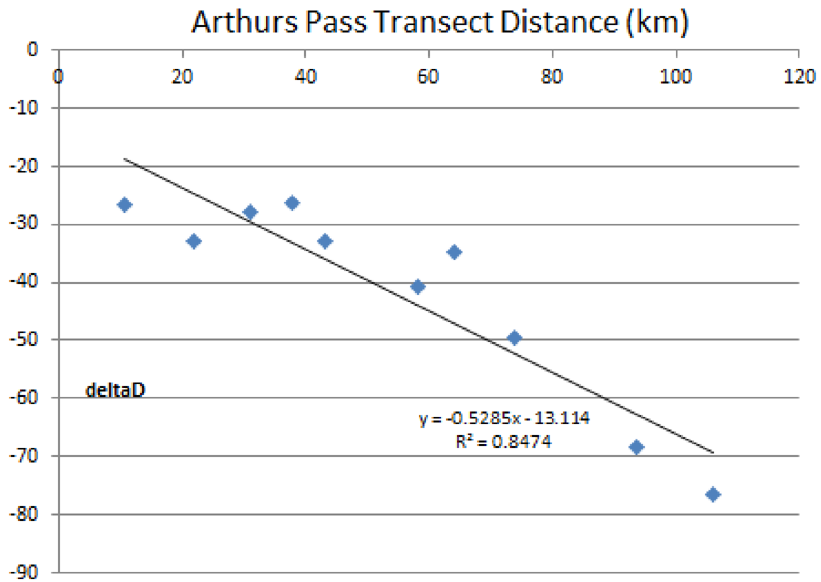


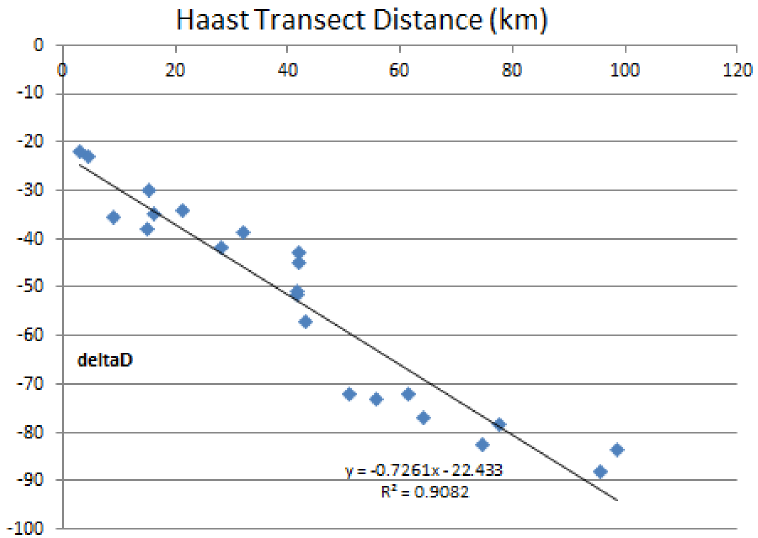
Southern Alps

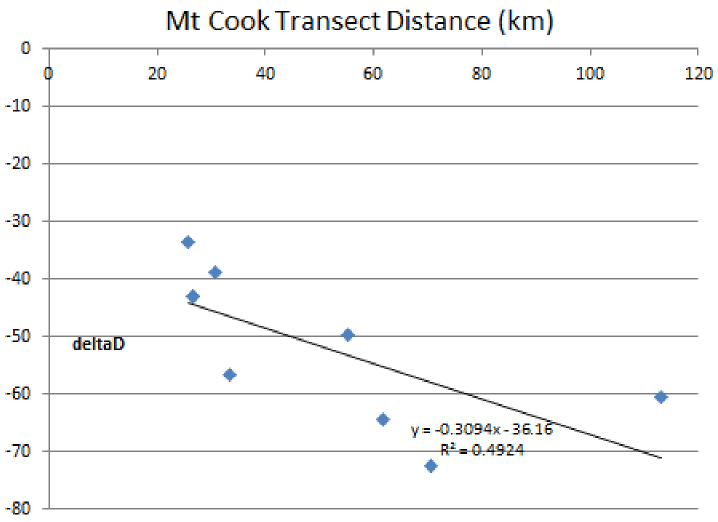
South Island, NZ

Arthurs Pass
Mt Cook
Haast

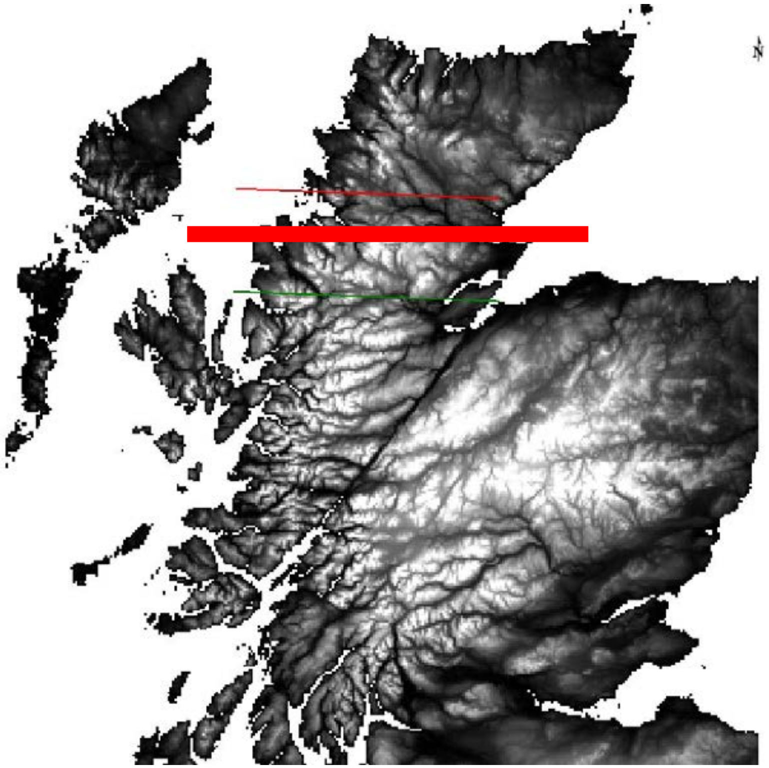


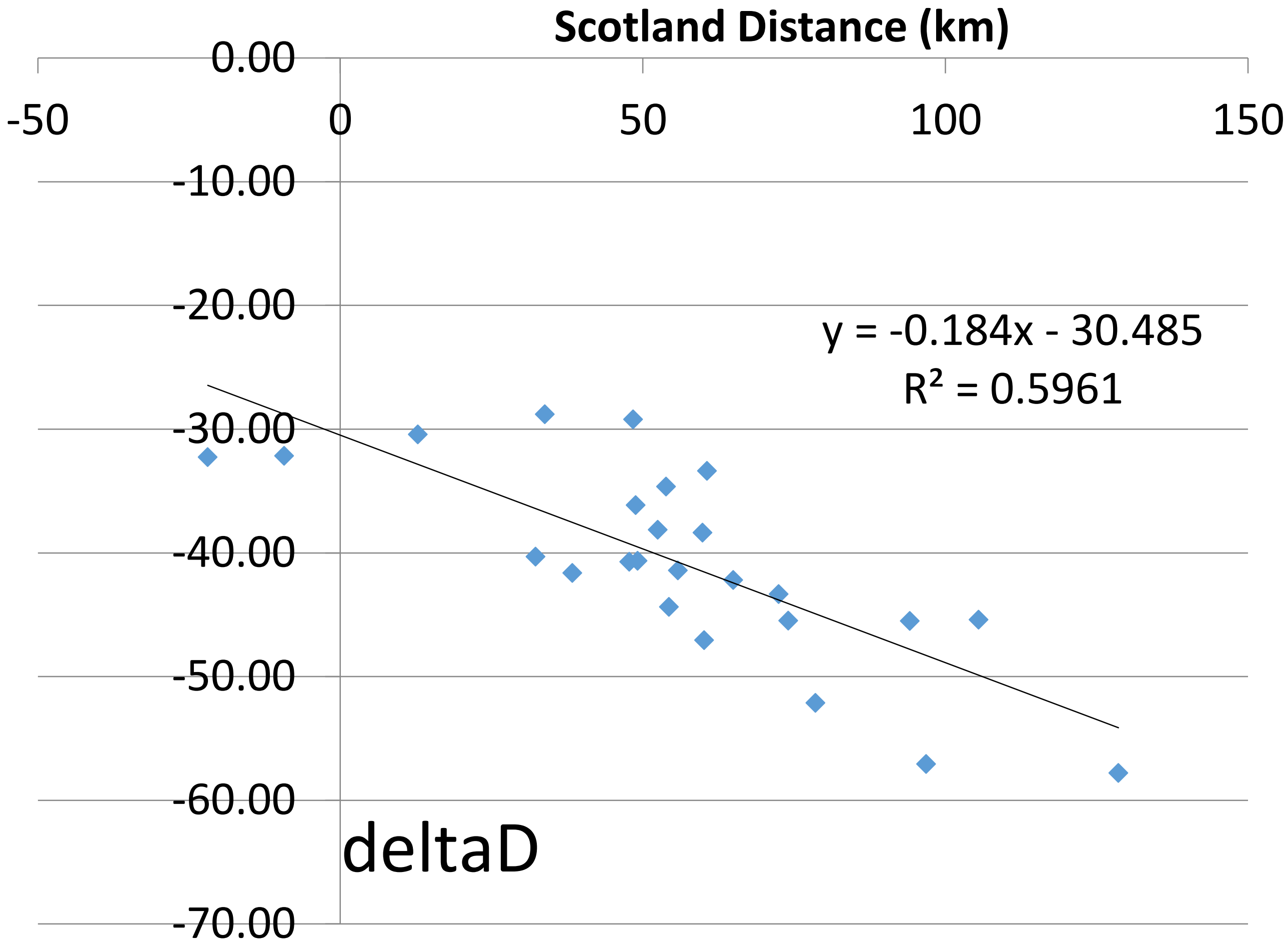




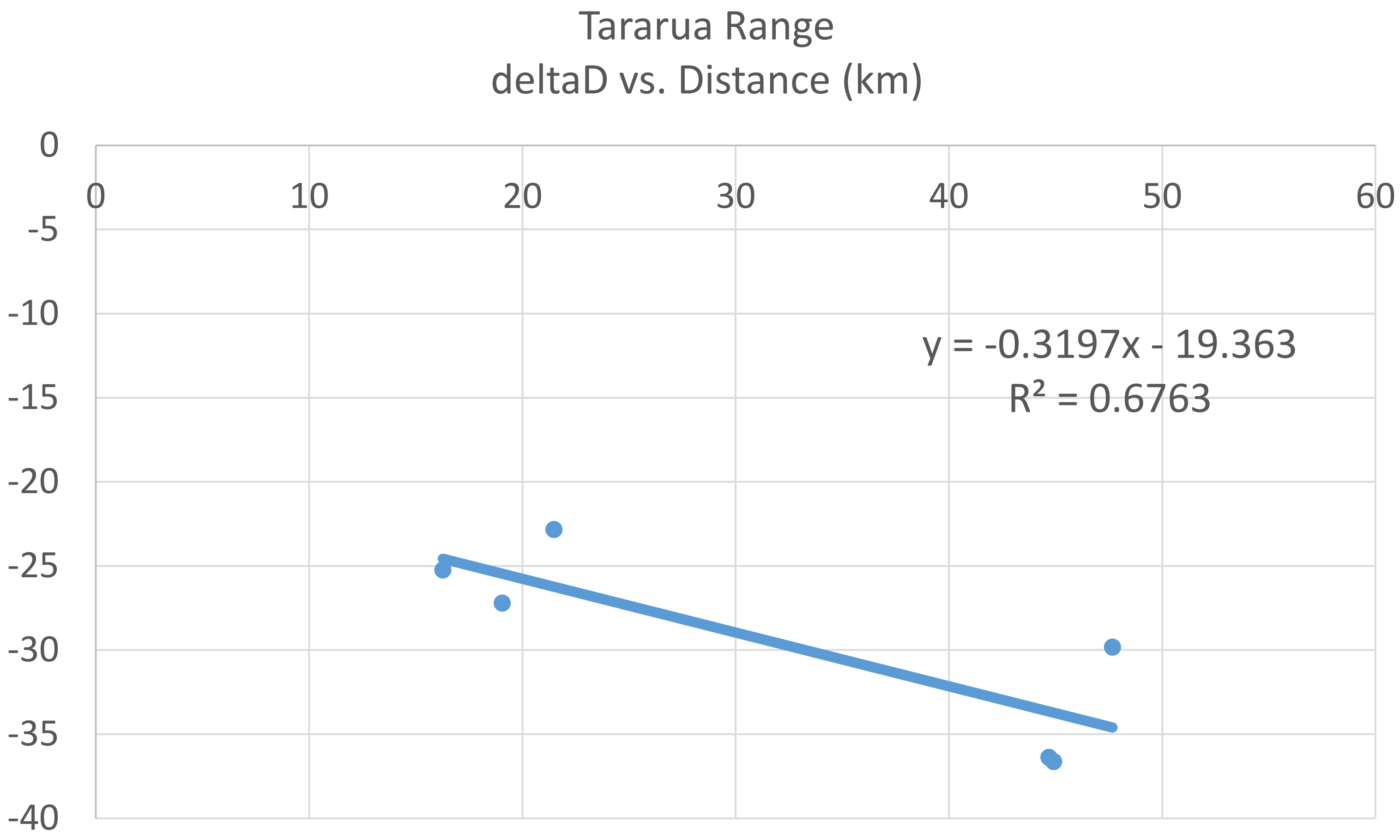


Scottish Highlands





Tararua Range, North Island, NZ



Cross-Mountain Isotope Differences (10 transects; Deuterium)

Range	Height (m)	delta D1	delta D2	Difference
Cascades	1400	-50	-110	-60
Andes N	1200	-30	-100	-70
Andes S	1200	-30	-100	-70
Sierra N	1700	-40	-100	-60
Sierra S	2200	-30	-110	-80
NZ Arthur	1200	-25	-75	-50
NZ Haast	1200	-25	-85	-60
NZ (Kerr 2015)	1200	-25	-80	-55
Scotland	400	-30	-55	-25
NZ Tararua	800	-25	-36	-11

Observed Isotope Fractionation by OP

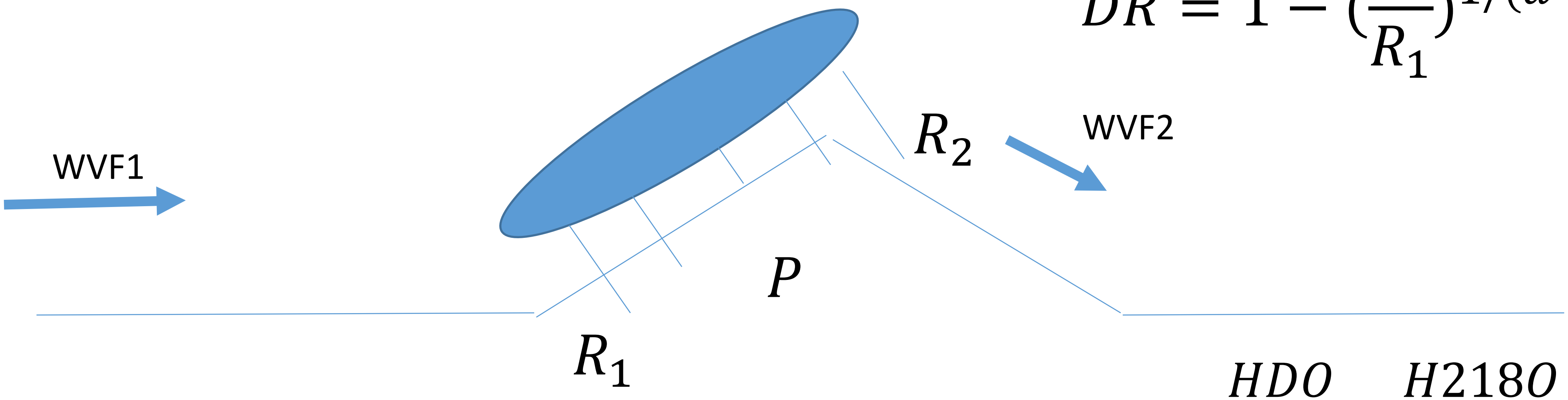
1. Orographic precipitation creates strong isotope gradients at constant latitude at mid-latitude sites.
2. Fractionation signal is robust and repeatable
    1. Different isotopes (D and 18O)
    2. Different water sources (Stream and Tree Stem)
    3. Parallel transects
    4. Repeat sampling (June and September)
    5. Different investigators
3. Fractionation increases with Mtn. Height

Drying Ratio=Fraction of water removed by OP

$$DR = \frac{WVF_1 - WVF_2}{WVF_1} = \frac{\Delta WVF}{WVF_1} = \frac{P}{WVF_1}$$

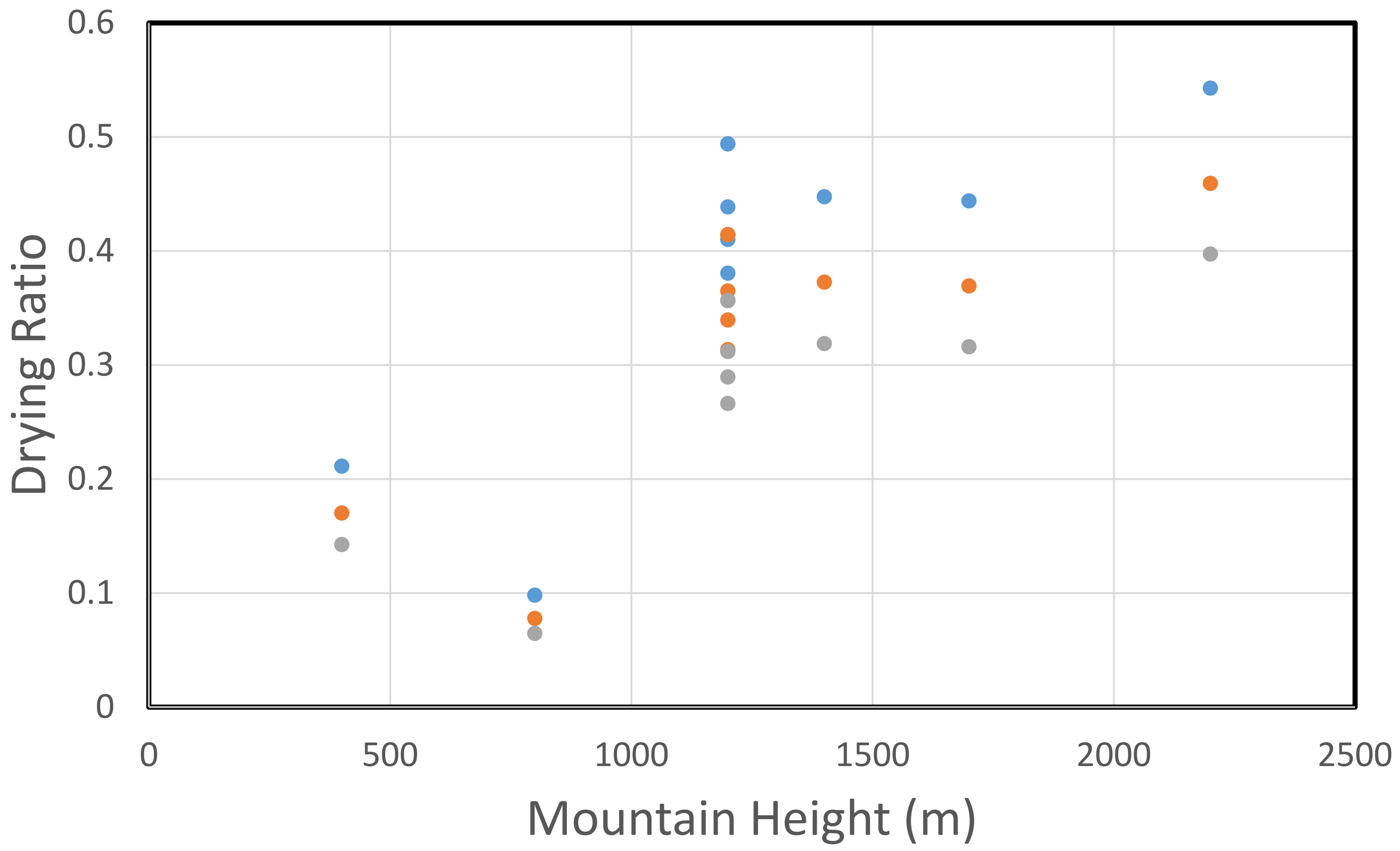
Rayleigh Fractionation

$$DR = 1 - (\frac{R_2}{R_1})^{1/(\alpha - 1)}$$



$$R = \frac{HDO}{H2O} = \frac{H218O}{H216O}$$

Drying Ratio vs. Mtn. Height
10 Transects; Deuterium, Rayleigh Fractionation



Alpha Values: Blue: $T = 0°\text{C}$ Red: $T = -20°\text{C}\ liquid$ Gray: $T = -20°\text{C}\ ice$

The "upslope" model of orographic precipitation

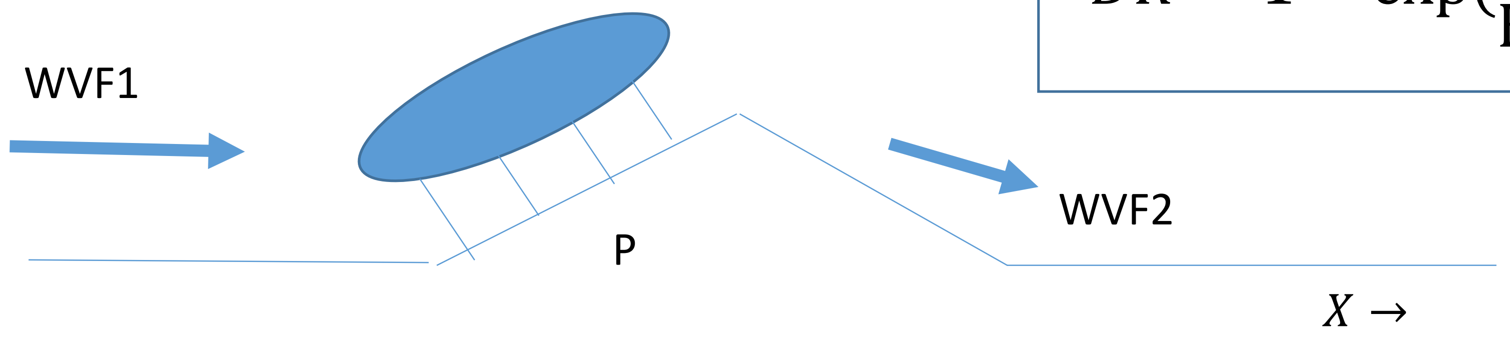
- Air flow at each level is parallel to the ground*
- Air is saturated with water vapor (Hsat)*
- Conversion of cloud droplets to precipitation is instantaneous*

$$P(x,y) = \frac{\overrightarrow{WVF} \cdot \nabla h(x,y)}{Hsat}$$

$$Hsat(T) \approx -R_W T^2 / L \gamma(T)$$

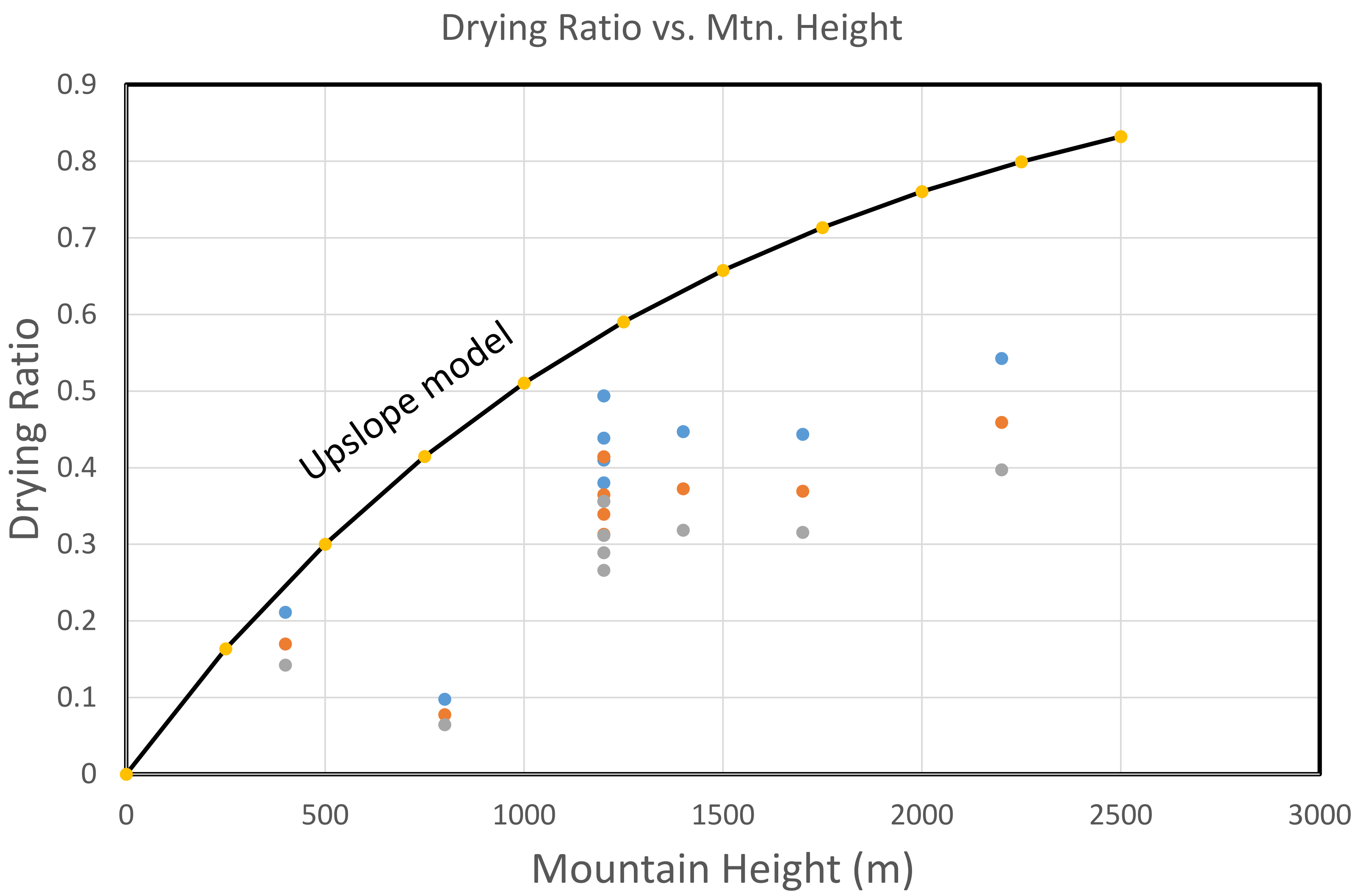
$$\gamma(T) \equiv moist\ adiabatic\ lapse\ rate$$

$$DR = 1 - \exp\left(\frac{-\mathrm{h}}{\mathrm{Hsat(T)}}\right)$$



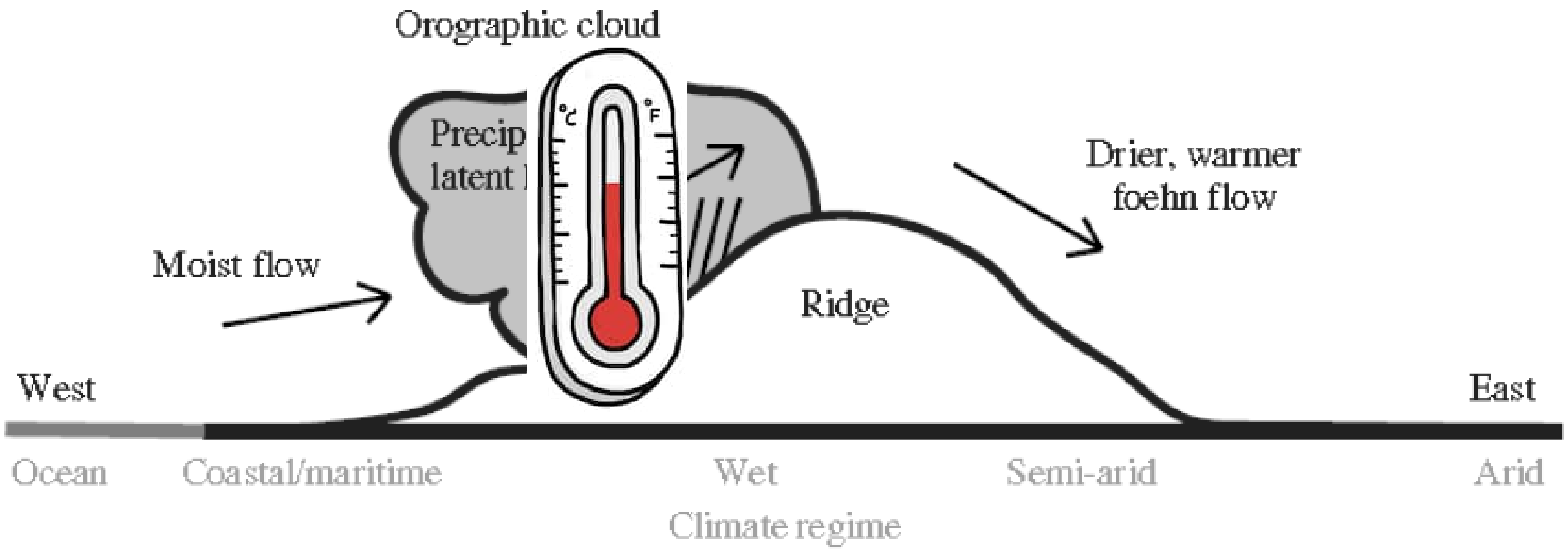
* These assumptions give an over-estimate of P and DR

Smith 2019



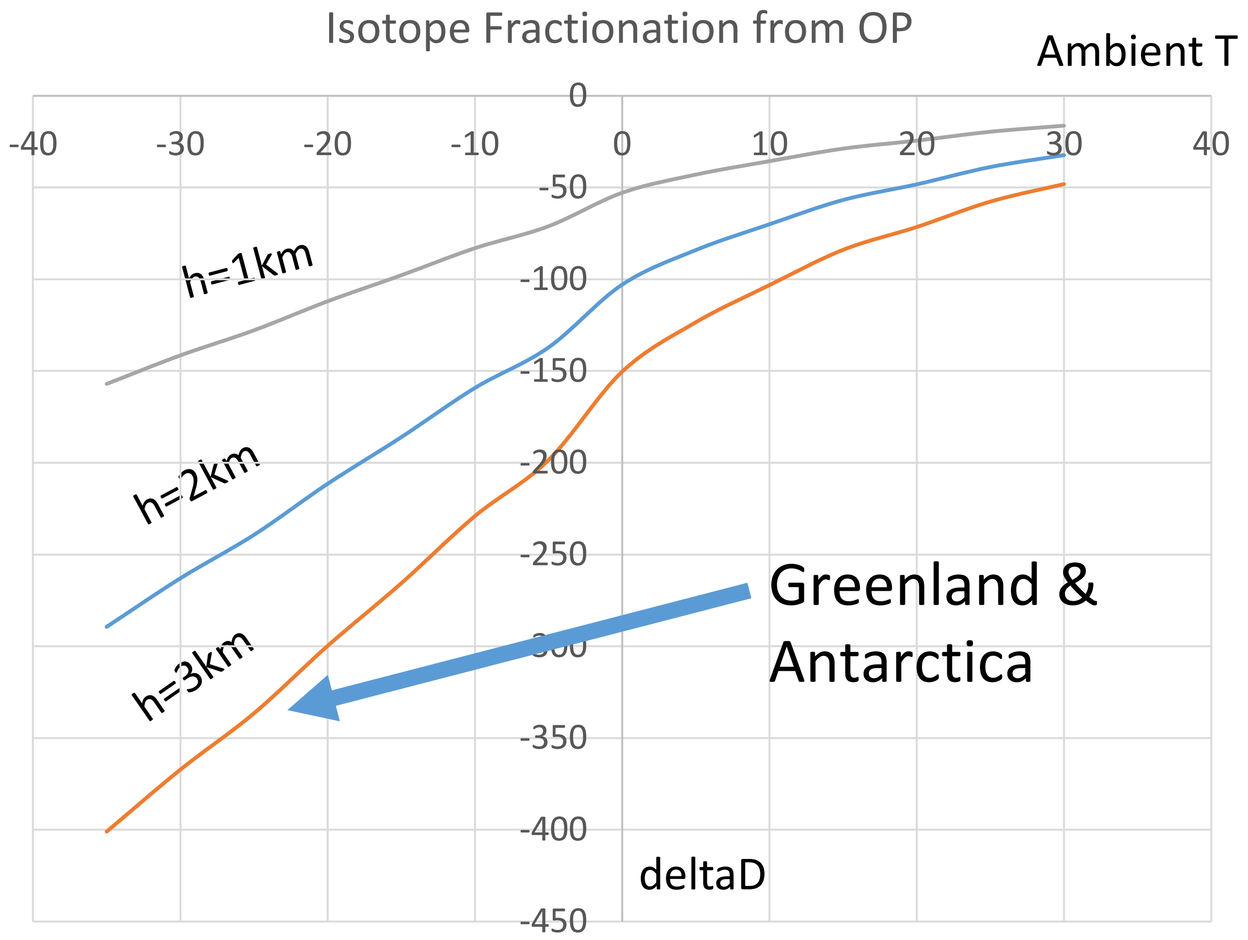
T = -10C; Hsat = 1400m

The orographic precipitation thermometer



Sensitivity of OP Fractionation to climate

1. Hsat increases with T
2. Alpha decreases with T
3. Sensitivity increases with height



These calculations were done
for deuterium; vapor to liquid fractionation.

Mtn. Height: Gray (h=1km); Blue (h=2km); Red (H=3km)

Open science questions

1. Do existing isotope-enabled models and global isotope data sets resolve the sharp spatial isotope gradients caused by orographic precipitation?
2. Are the isotope derived Drying Ratios accurate?
3. What physical processes must be included to accurately predict OP fractionation: convection, ice-phase microphysics, 3-D blocking?
4. What fraction of the Pleistocene ice core climate record on Greenland and Antarctica is a local signal; derived from the orographic precipitation as the air climbed about 3km onto the ice sheet?

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