

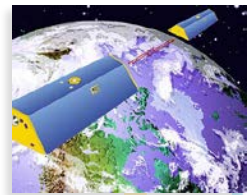
Que sabemos de precipitación orográfica?

Lecciones de la cordillera de Nahuelbuta

René D. Garreaud^{1,2}, Mark Falvey^{1,3}, Aldo Montecinos^{4,5}

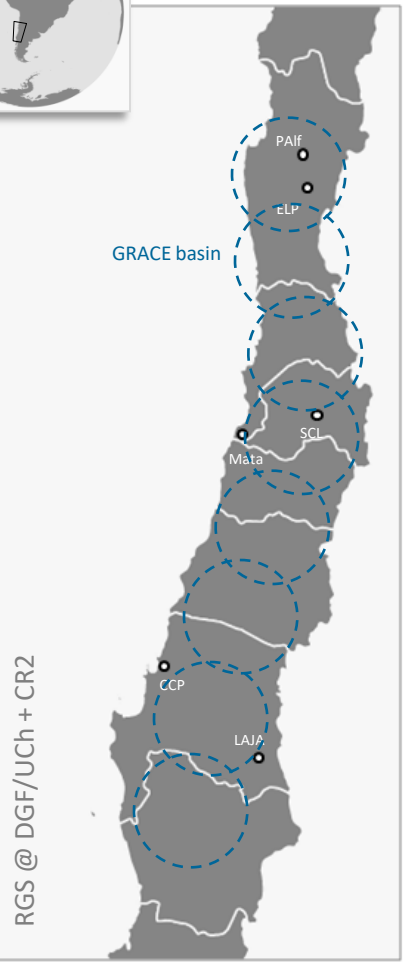
*Cristian Muñoz, Andrés Arriagada, Cinthya Bravo,
Sergio Gonzalez, Freddy Echeverria, Conaf,
Escuela Trongol Alto, Escuela Oscar Muñoz, Liceo Curanlihue*

1. Departamento de Geofísica; 2. Centro de Ciencia del Clima y la Resiliencia CR2
3. Meteodata; 4. Universidad de Chile-Universidad de Concepción; 5. CHRIAM

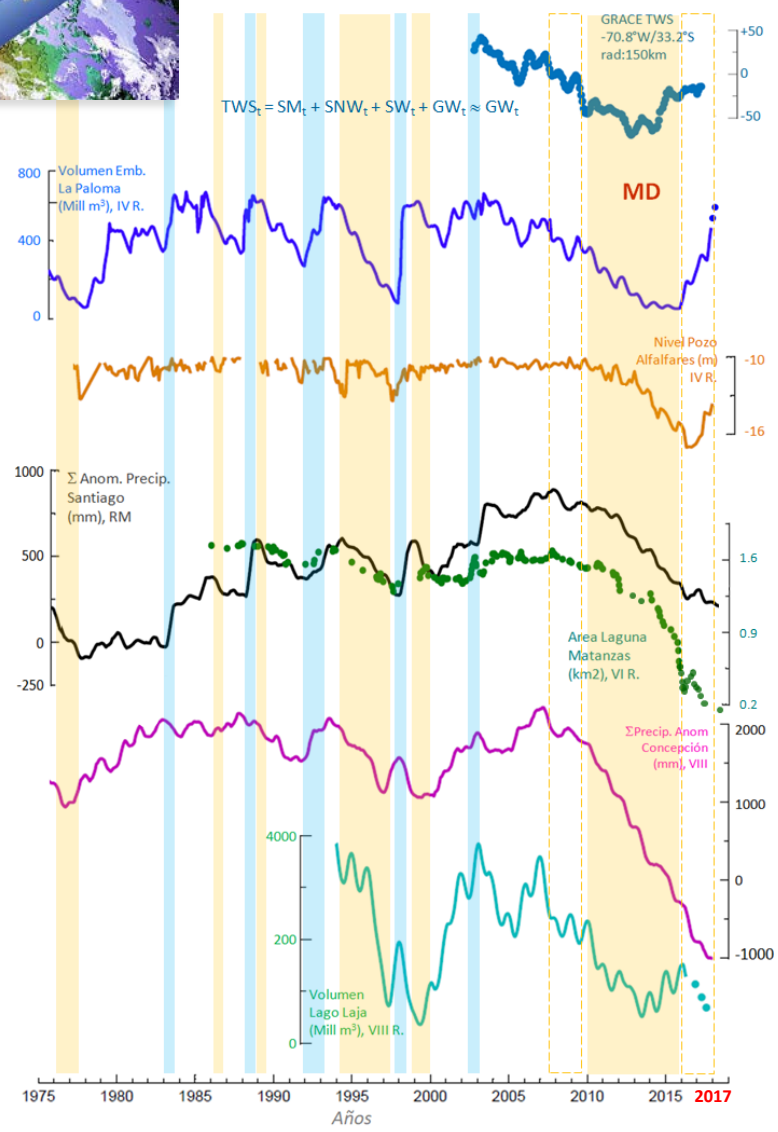


31°S

39°S



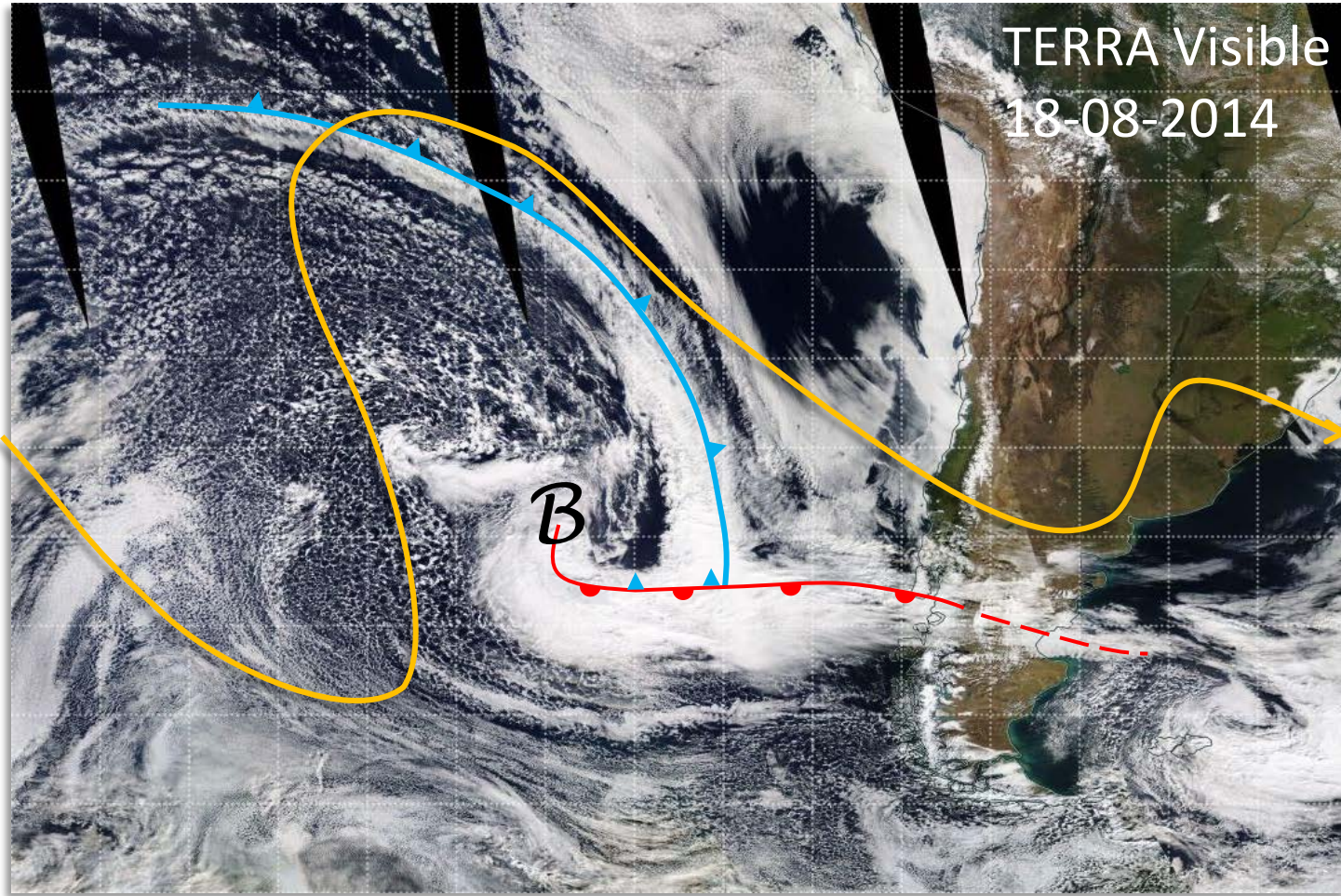
71°W



Estructura

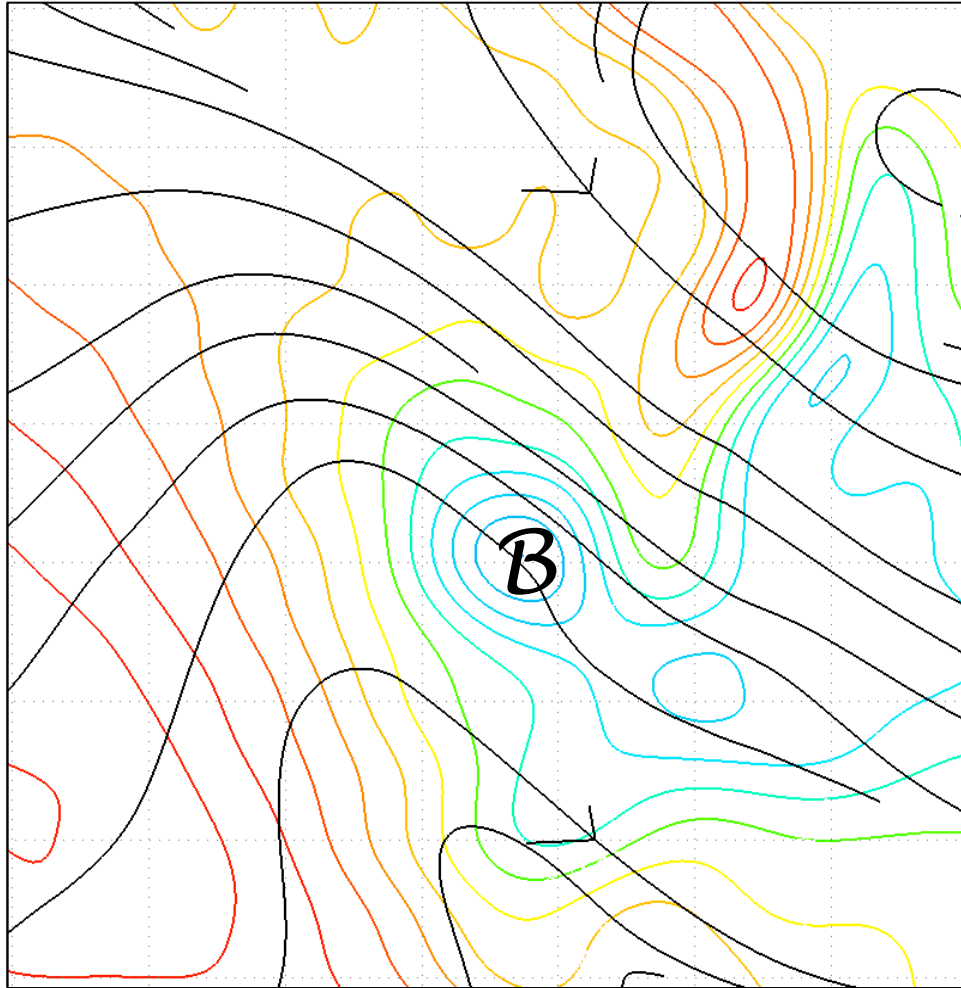
- Motivación (que NO sabemos)
- El proyecto AFEX (mal nombre!)
- Precipitación orográfica en Nahuelbuta
 - Condiciones medias
 - Variabilidad intra tormenta
 - Linealidad
 - Microfísica
- El campo de temperatura sobre Nahuelbuta.

Un ejemplo de texto de un sistema frontal.
Donde esta lloviendo?



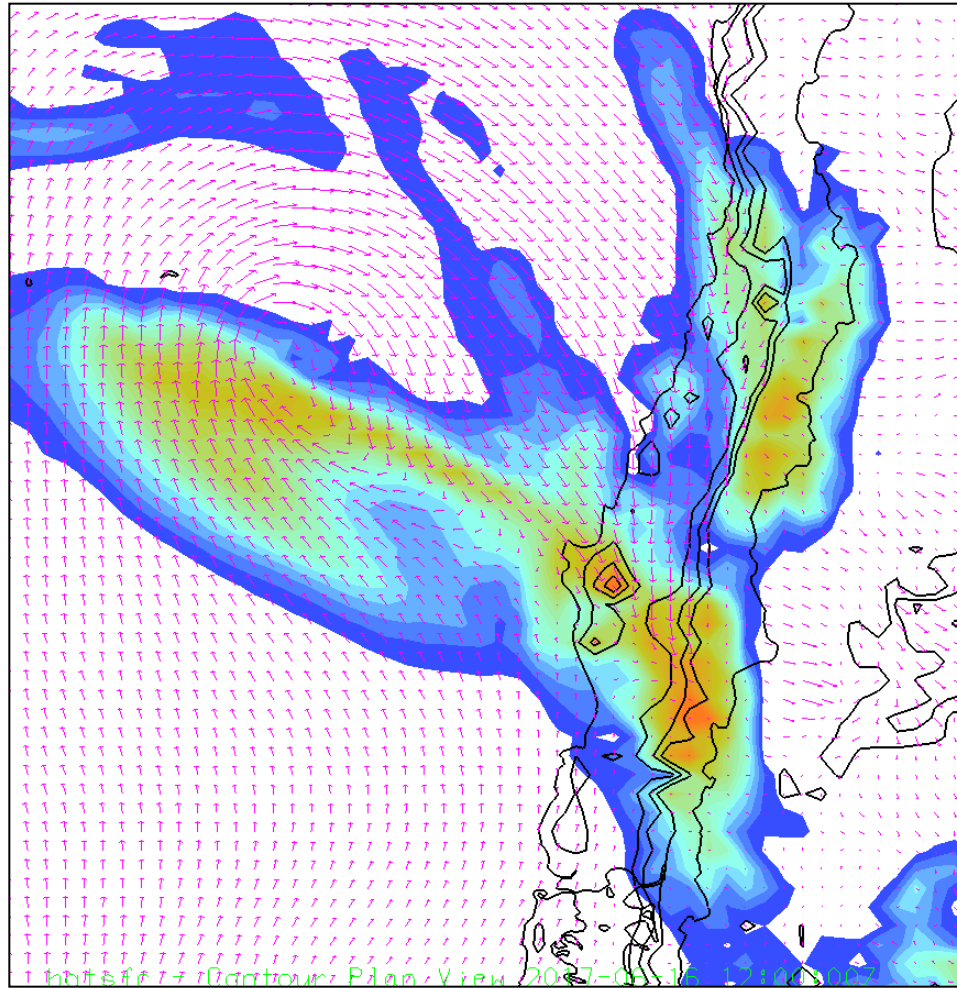
GFS 0.25 – Initial time: 00Z 16 June 2017 – Valid: 12Z 16 June 2017

PNM + V500. Donde esta lloviendo?



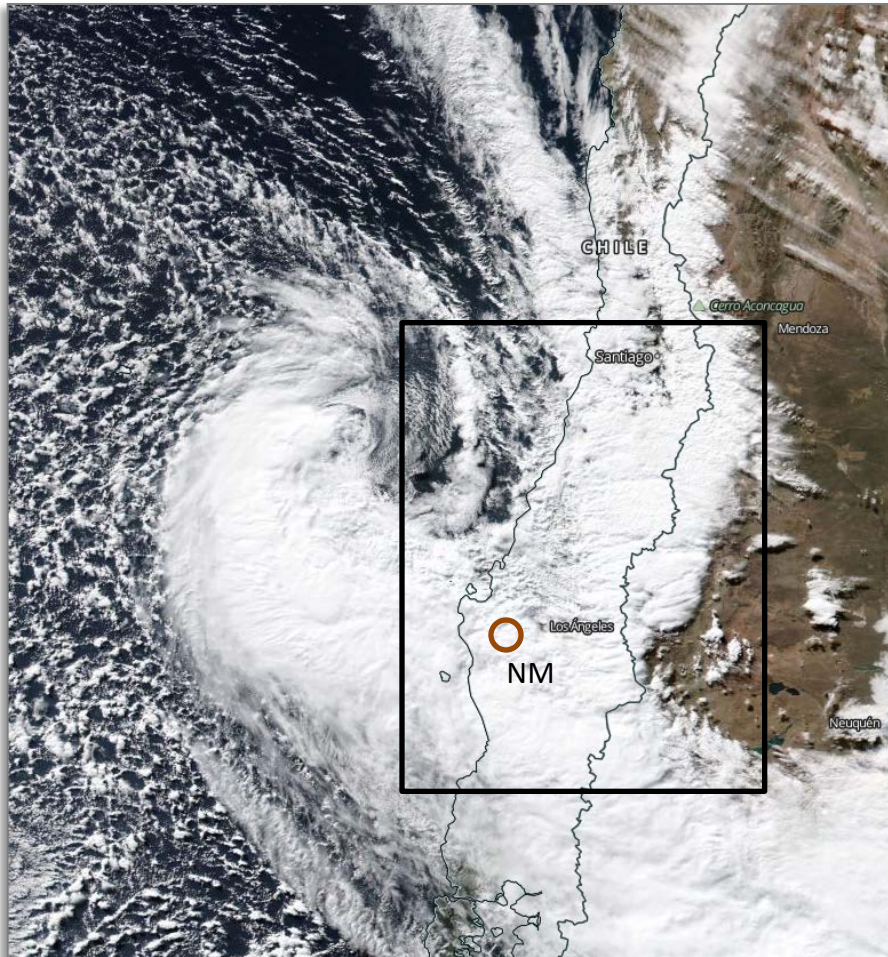
GFS 0.25 – Initial time: 00Z 16 June 2017 – Valid: 12Z 16 June 2017

Prec6h + V900 + Terrain

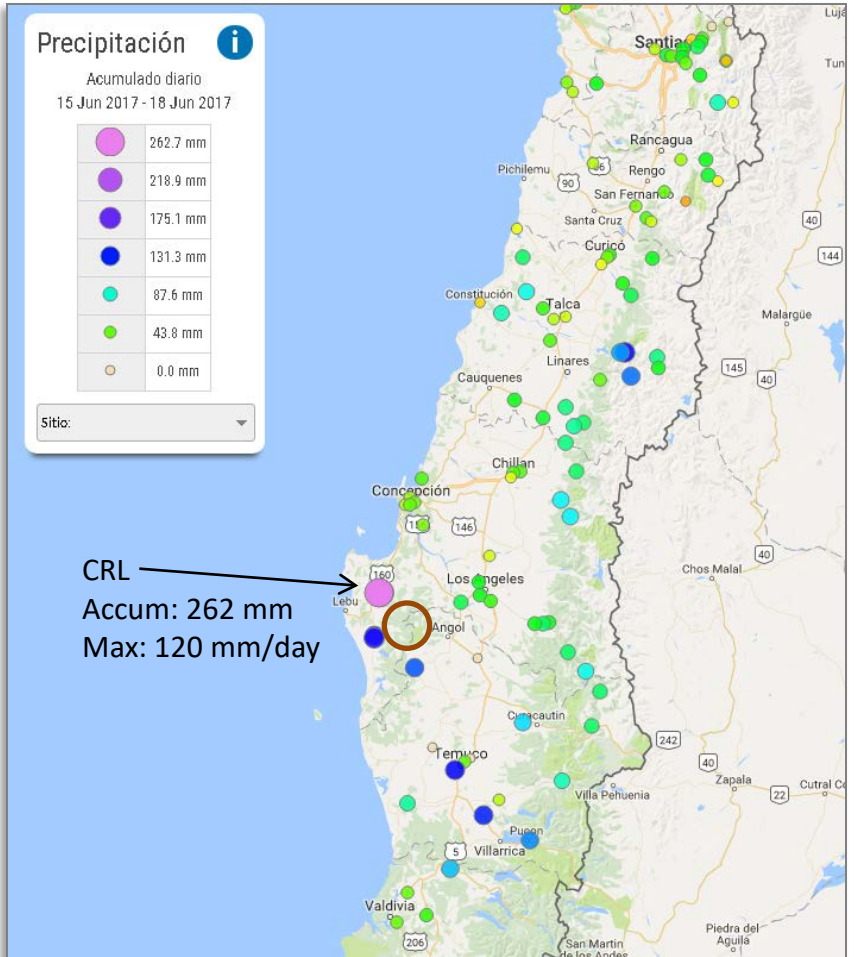


Las cosas se complican en presencia de la orografía

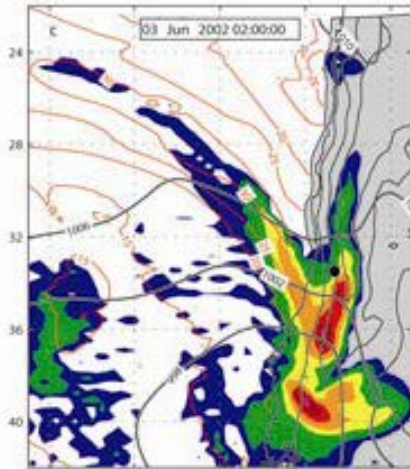
(a) MODIS Terra VIS, 17 June 2017



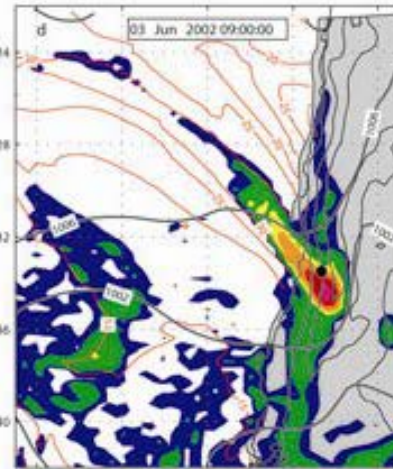
(b) Storm accumulation (15-18 June 2017)



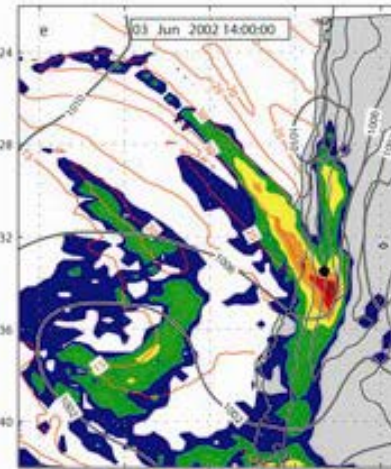
Impacto de la topografía en la evolución y estructura frontal. Simulaciones WRF (Mark Falvey), Junio 2002



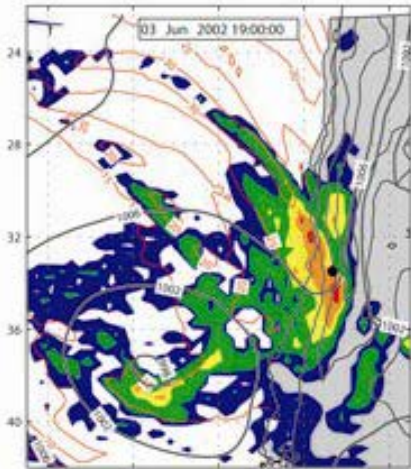
0200 UTC



0900 UTC

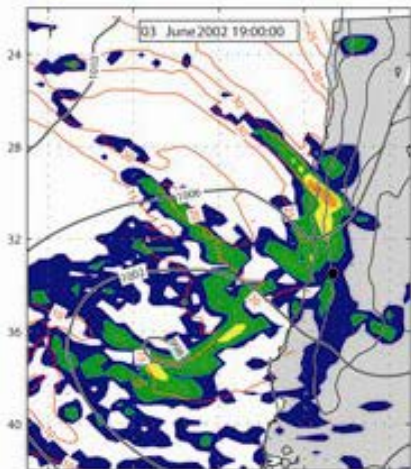
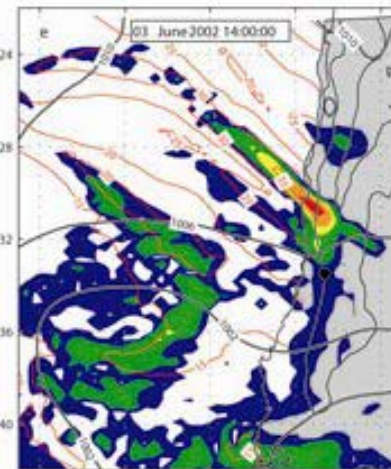
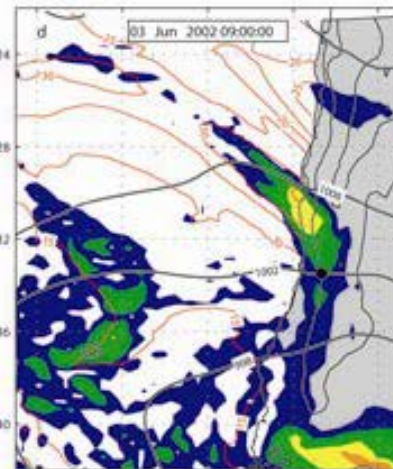
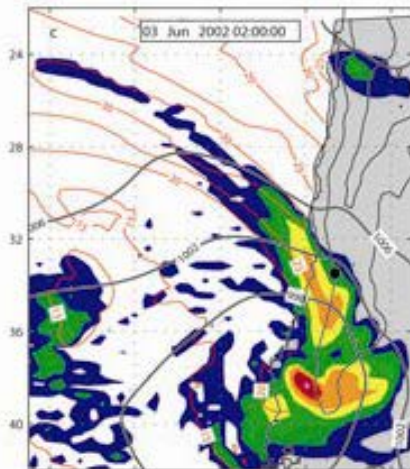


1400 UTC



1900 UTC

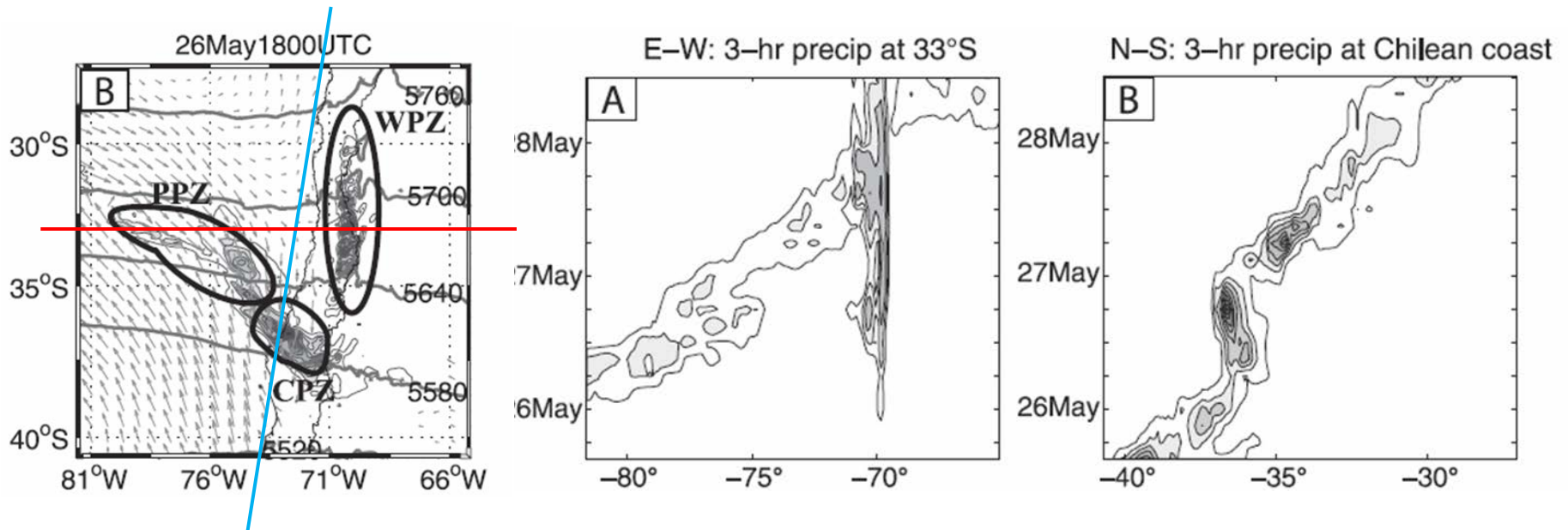
Topo 100%



Topo 40%

Impacto de la topografía en la evolución frontal:

- Fractura frontal (océano-continente) y desaceleración
- Precipitación prefrontal en cordillera (?)
- Incremento de la precipitación sobre la cordillera (**Intensidad, duración o ambos?**)

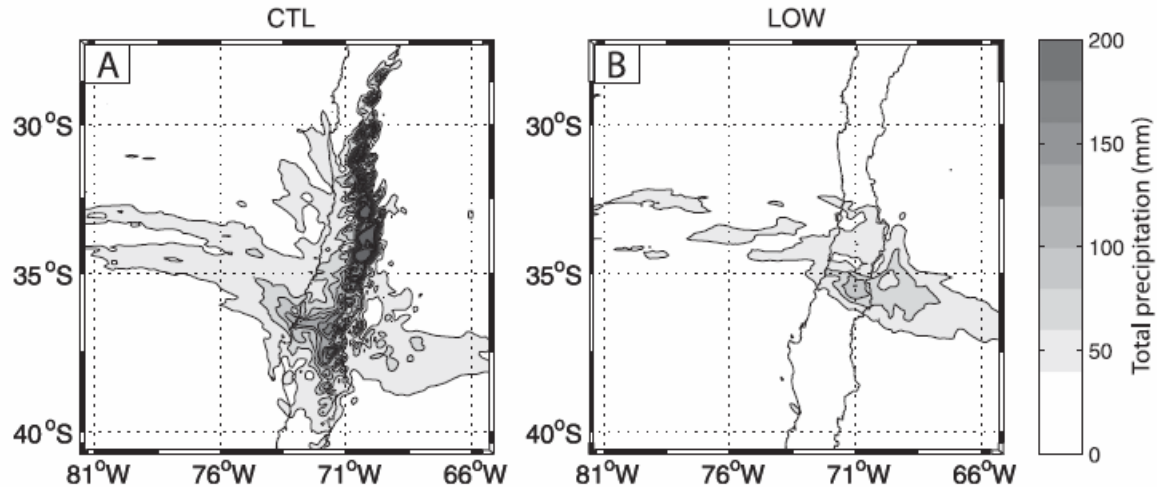


Impacto agregado de la topografía en la evolución frontal: Incremento de la precipitación sobre la cordillera (Intensidad, duración o ambos?)

SEPTEMBER 2009

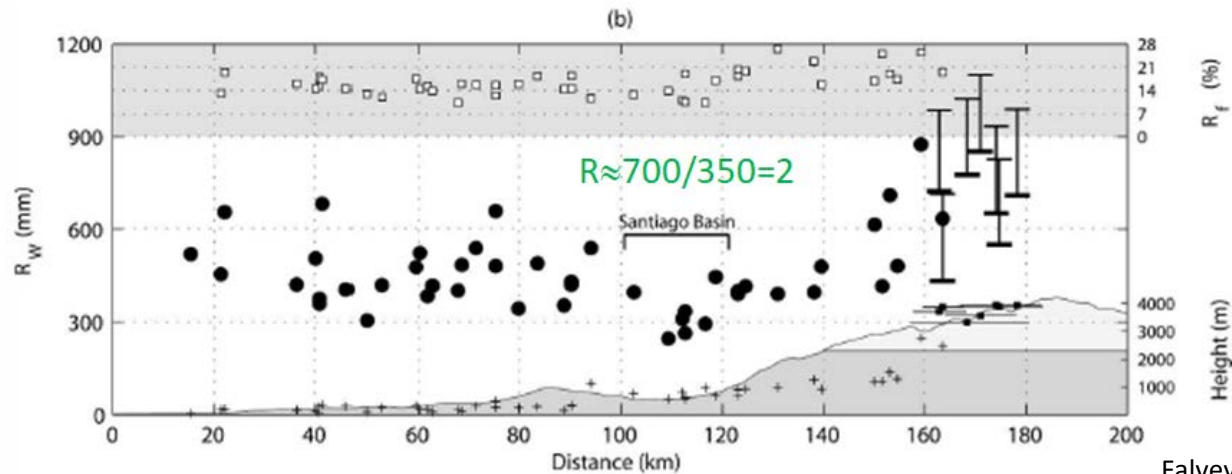
BARRETT ET AL.

3107



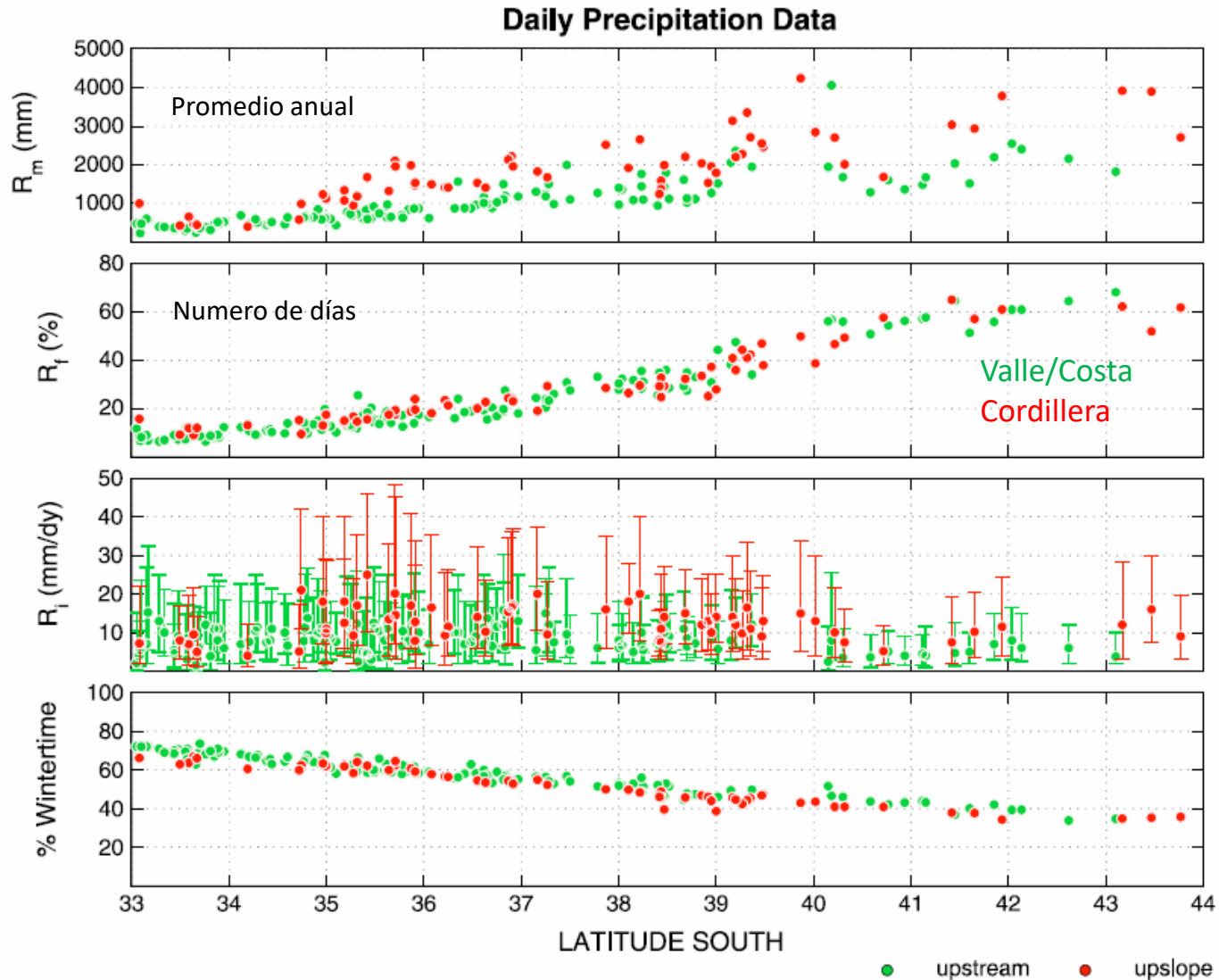
Barret et al. 2009

FIG. 13. Total precipitation from the (a) CTL and (b) LOW simulations.



Falvey and Garreaud 2007

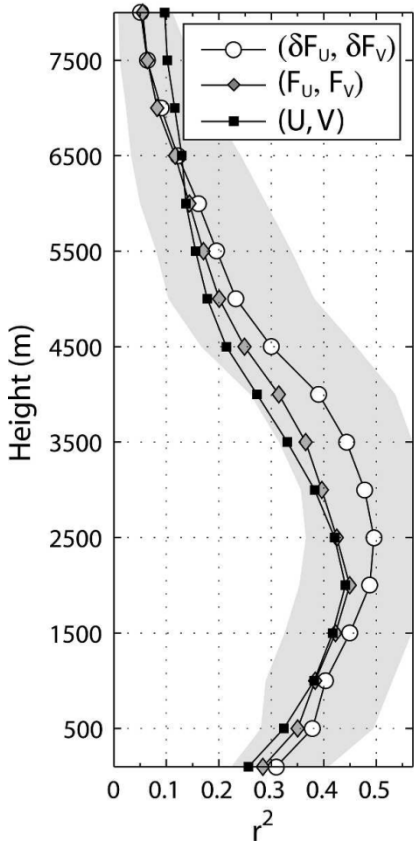
Impacto agregado de la topografía en la evolución frontal: Incremento de la precipitación sobre la cordillera (Intensidad, duración o ambos?) Viale and Garreaud 2015



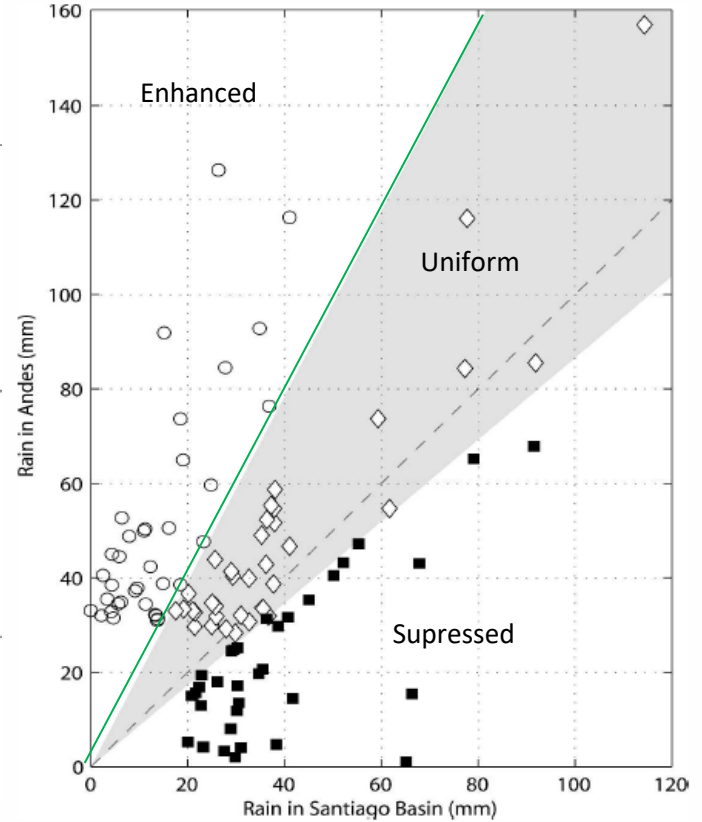
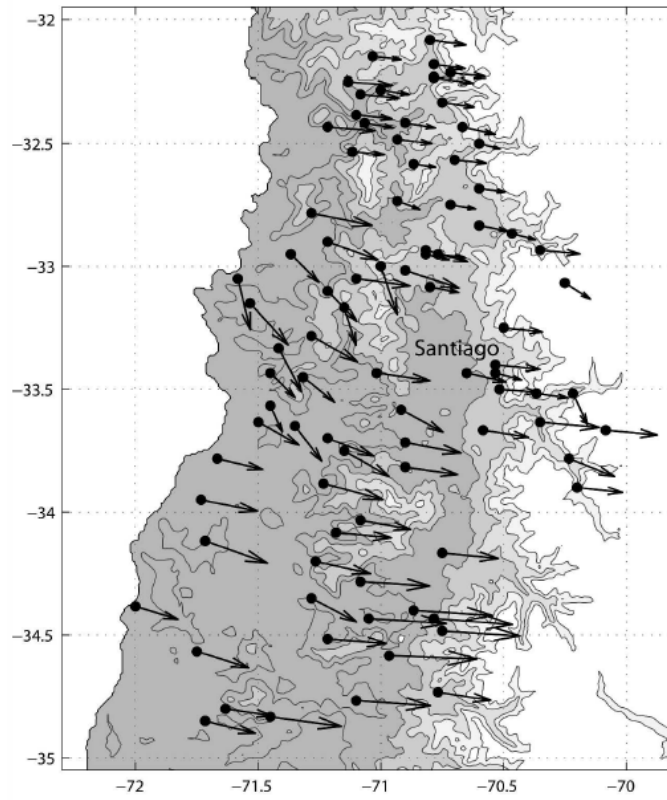
Pregunta pendiente (y muy relevante)

Que controla el GOP en entre/intra tormentas?

$r[P^*, U(z)]$



$r[P, U(2500\text{ m})]$



Hasta el 2011 sabíamos :

- Acumulación anual se incrementa con la altura
- Incremento orográfico mas o menos uniforme con latitud!
- Numero de días con precipitación no varía con altura
- Acumulación diaria/regional depende del flujo zonal

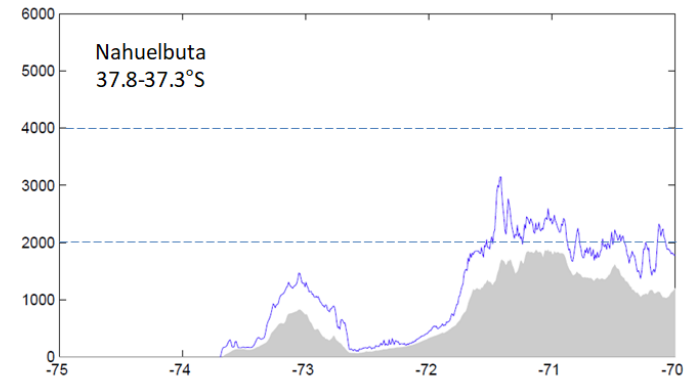
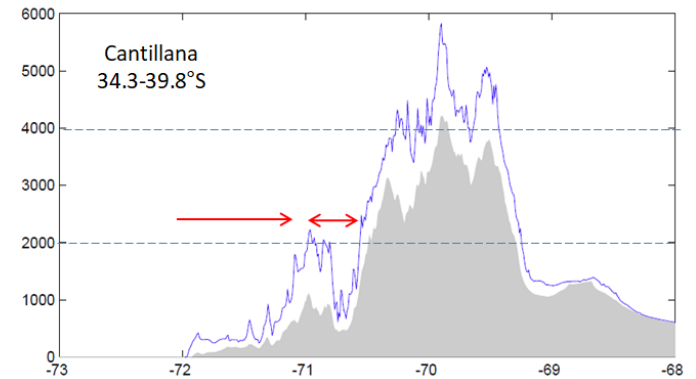
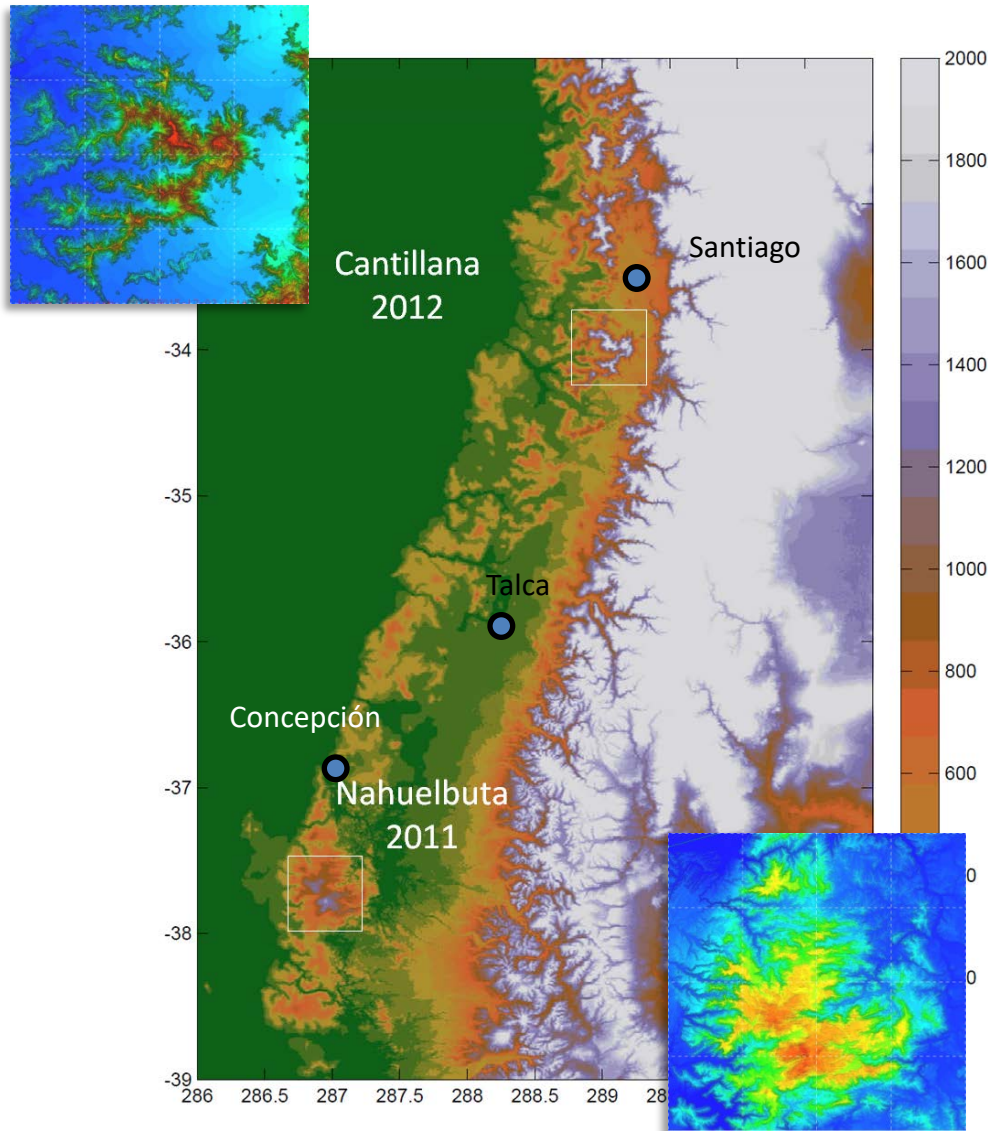
Para entender en detalle los efectos de la perturbación orográfica en la distribución de la precipitación ($GOP(t)$) necesitamos al menos:

- Una densa red de instrumentos en altura
- Mediciones de lluvia y nieve
- Resolución horaria o menor
- Un buen modelo

*Complicado....
vamos a la costa*

Efectos de la topografía en la precipitación de Chile central

René Garreaud, Mark Falvey, Aldo Montecinos



Bloqueo orográfico

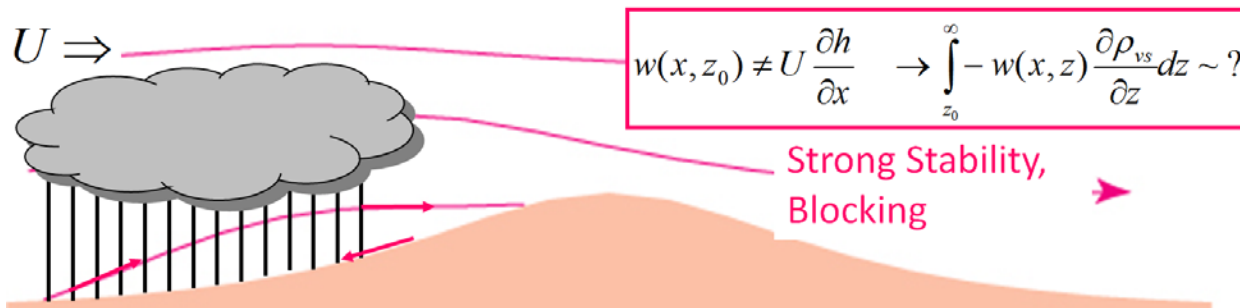
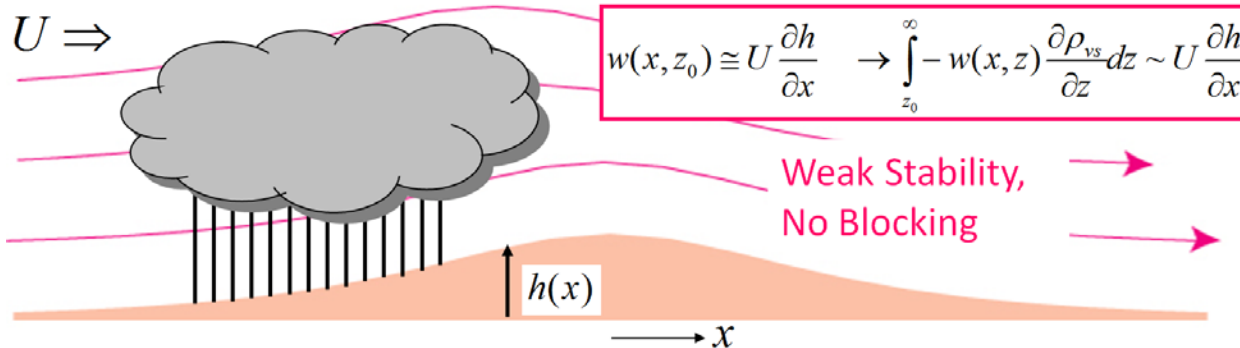
El numero de **Froude** determina flujo sobre/flujo alrededor de la montaña

$Fr=U/(Nh)$; $Fr<1$ flujo alrededor; $Fr>1$ flujo sobre

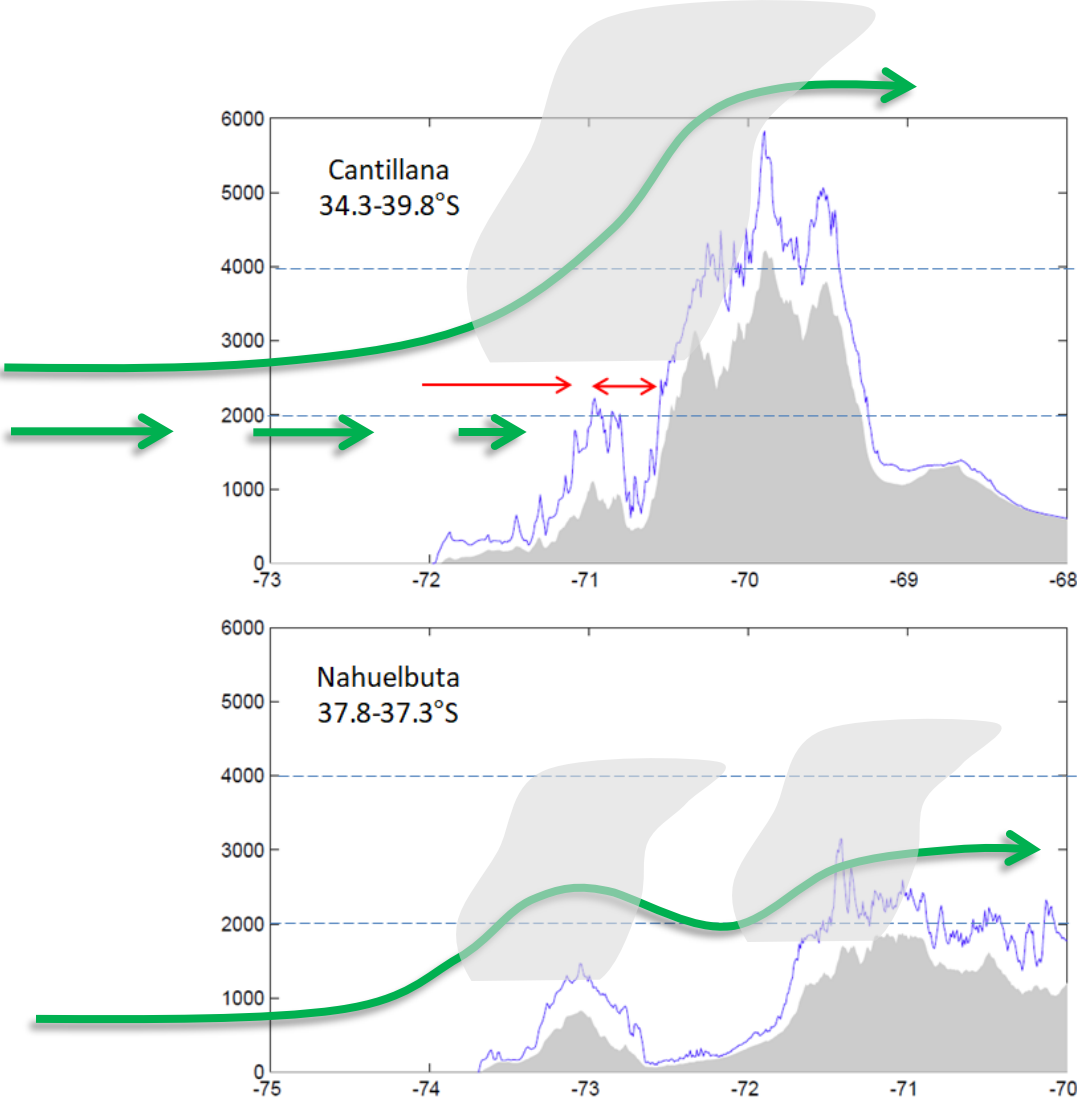
Si $N=0.01$, $U=10$, $h=1$ km es el limite

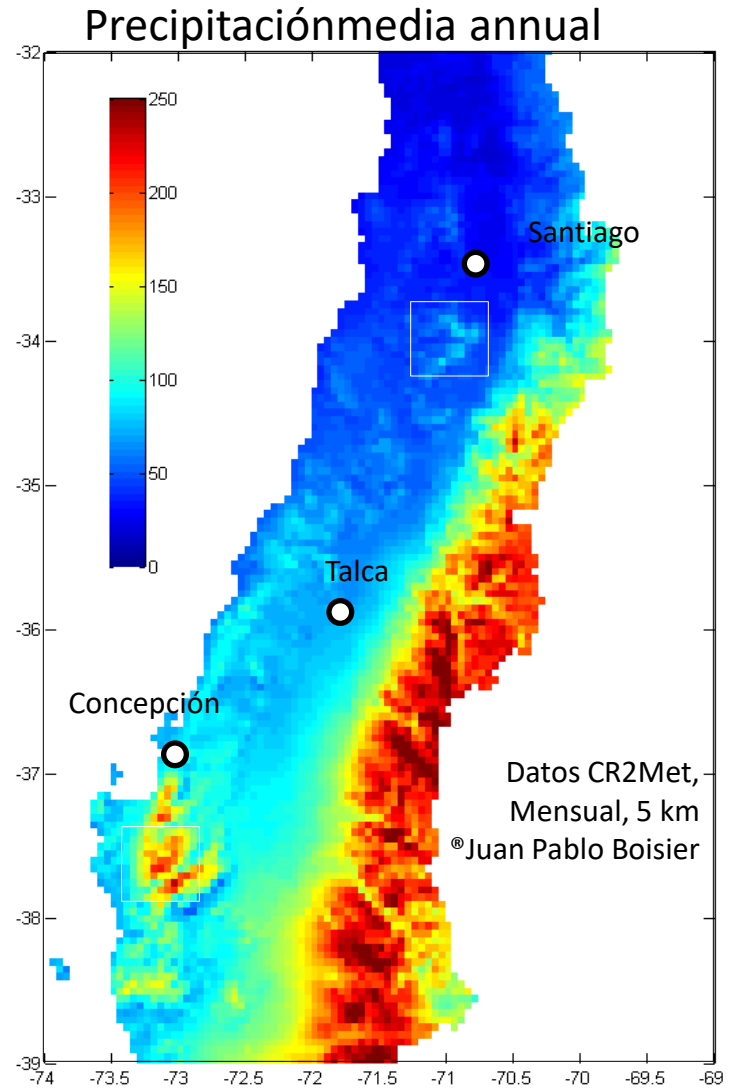
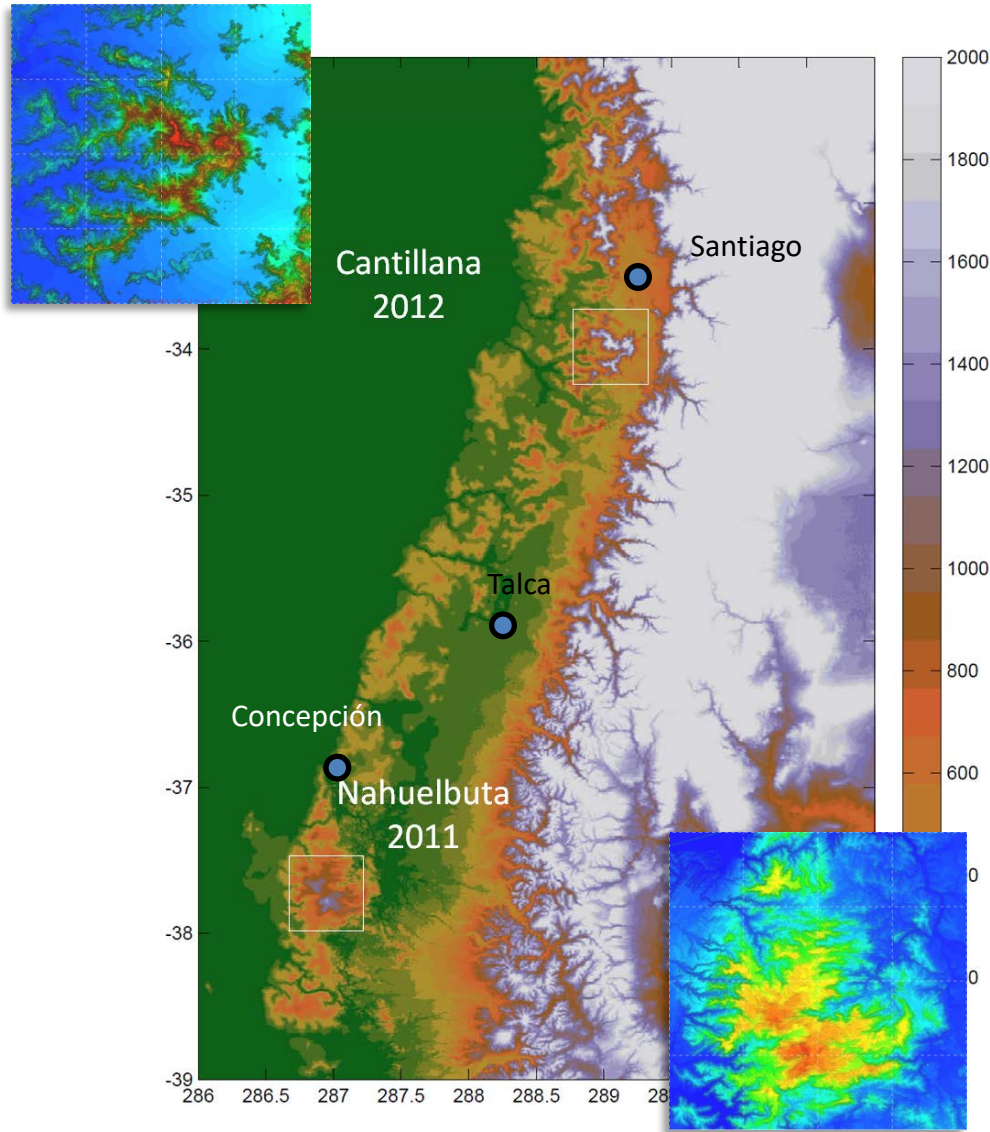
En caso saturado se emplea $N_m < N$ lo cual favorece ascenso sobre la montaña

Dynamics: Stable Flow



Deberían existir diferencias importantes en la modificación orográfica producida por Cantillana (subtropical) y Nahuelbuta (Latitudes medias)

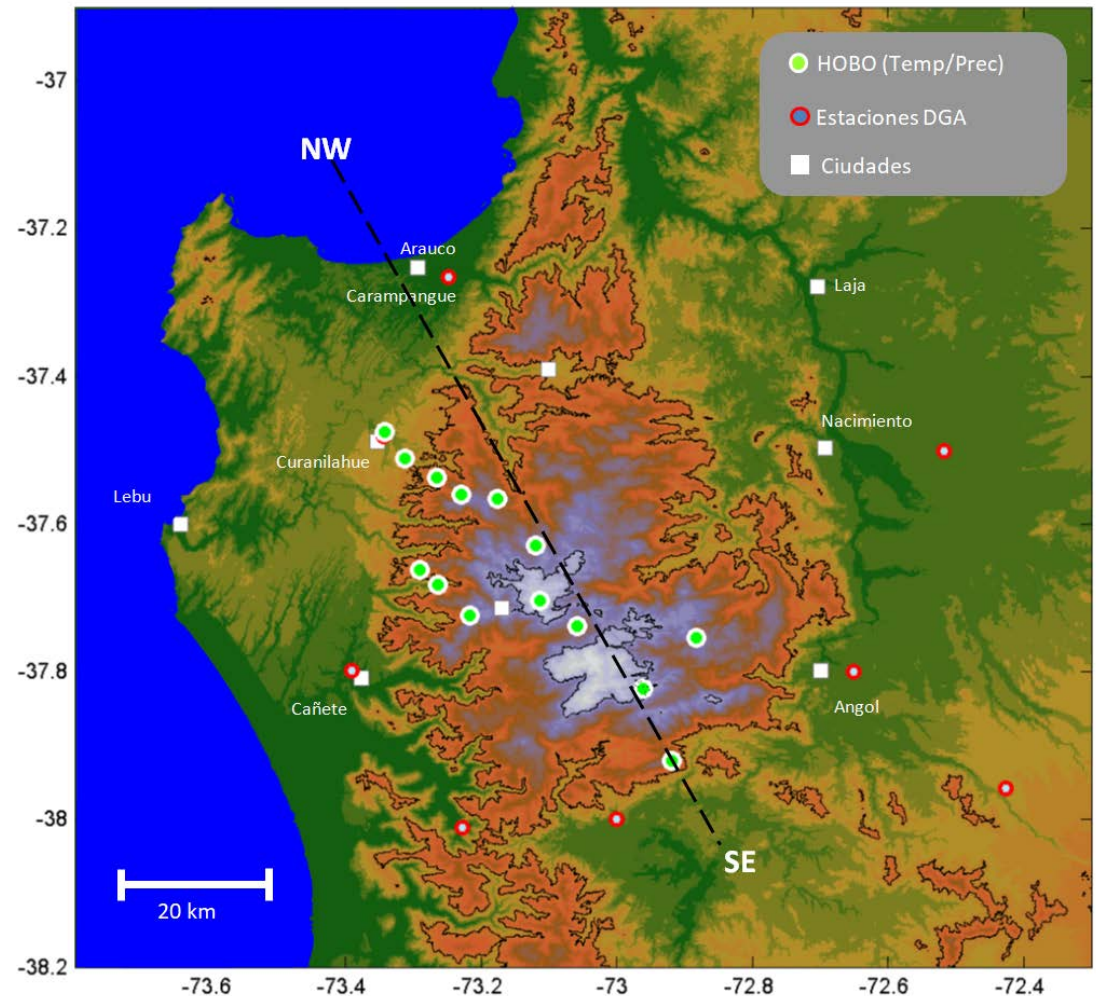
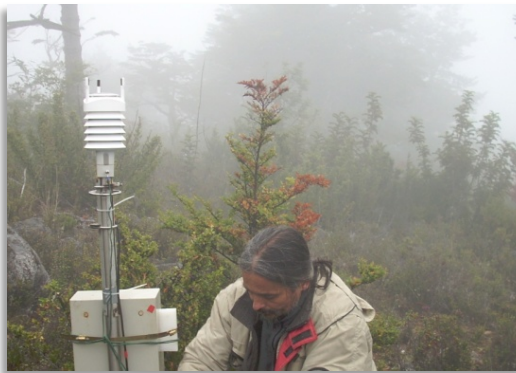




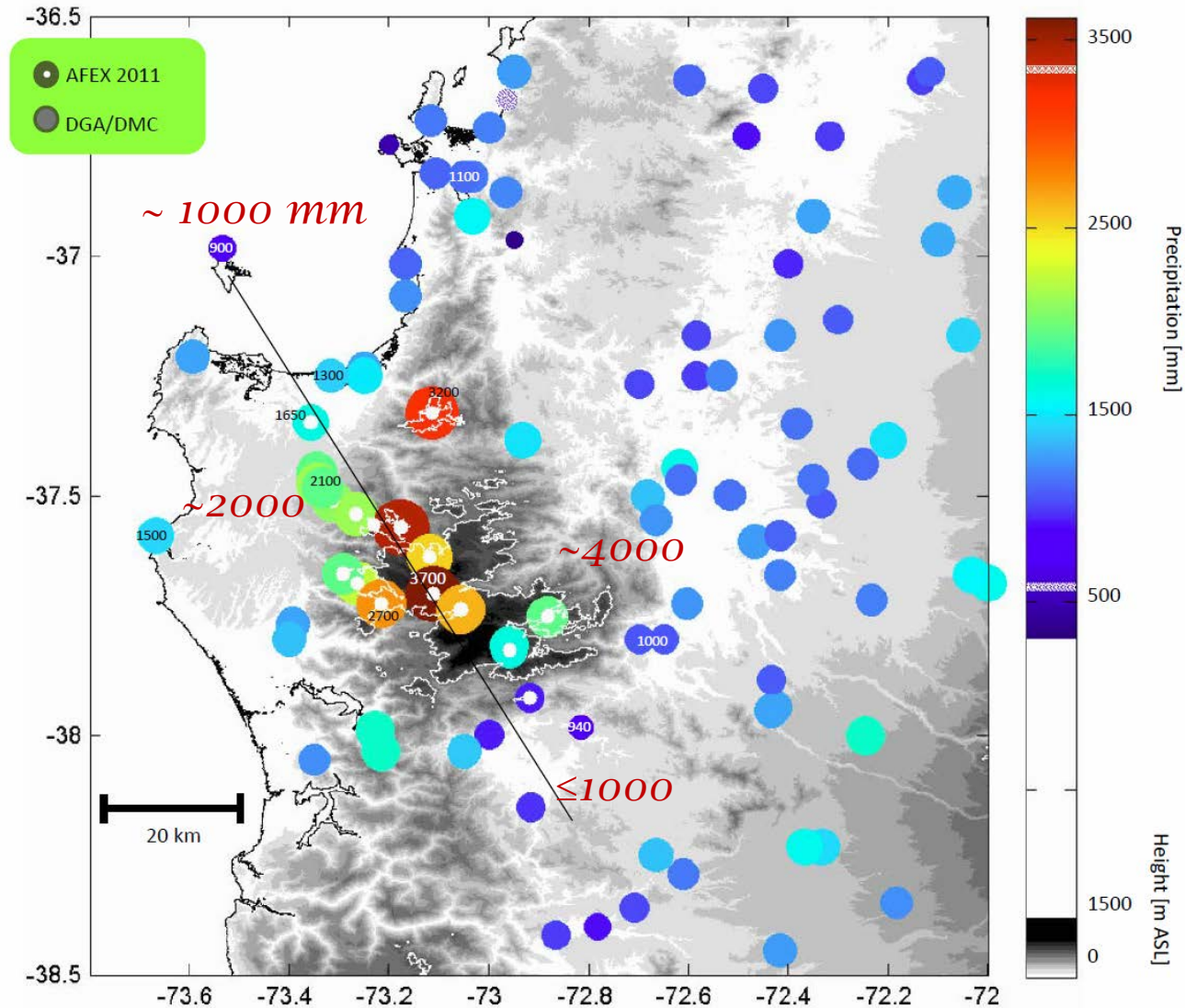
Meso-red de termo-pluviómetros en la cordillera de Nahuelbuta

14 HOBO RG-3M, 10 min Ta & 0.2 mm
01 Estación Vaisala (Ta, HR, V, R)

02 Junio – 26 Sep. 2011 → 2013

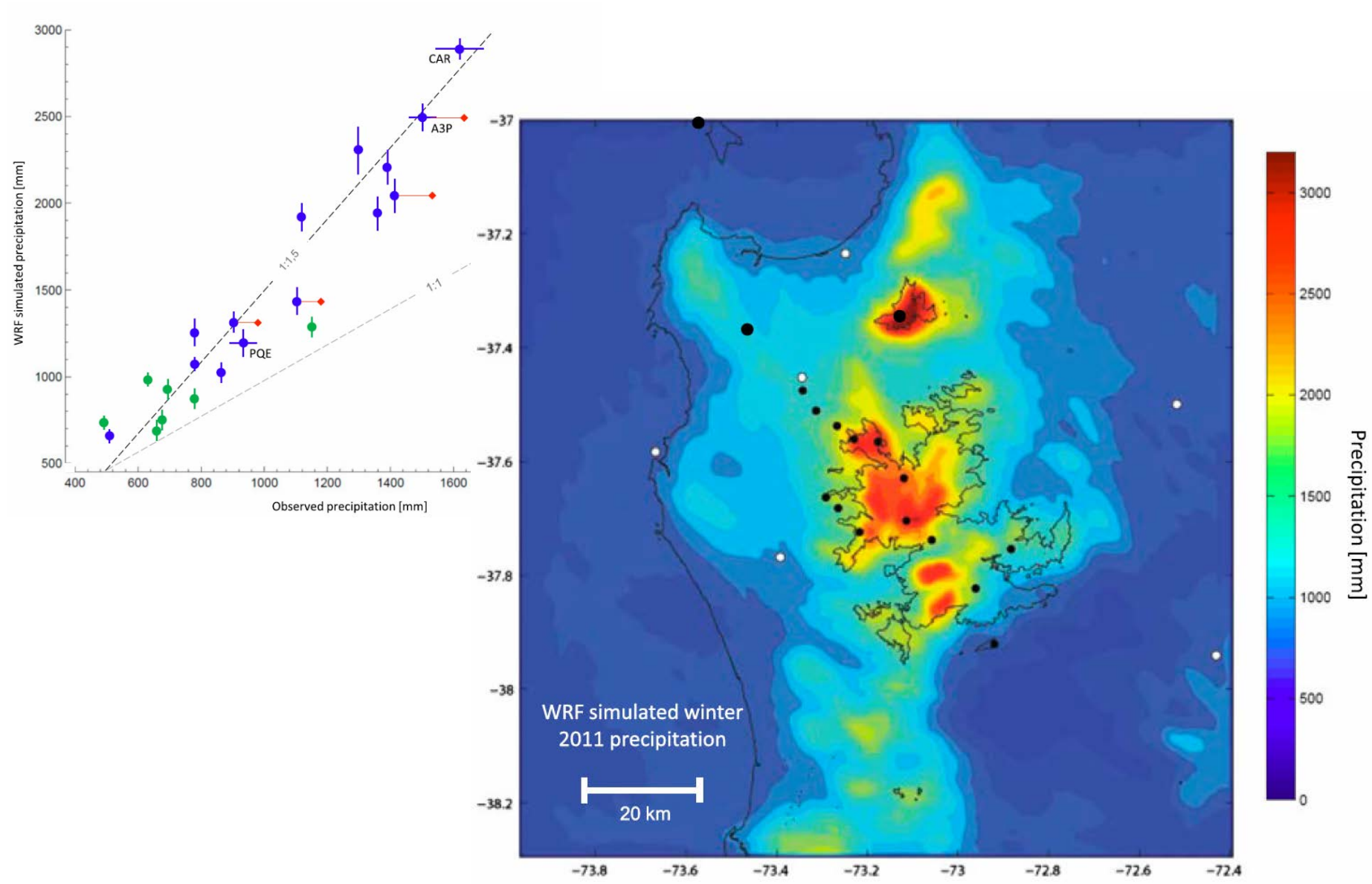


Estimated annual mean precipitation [mm]



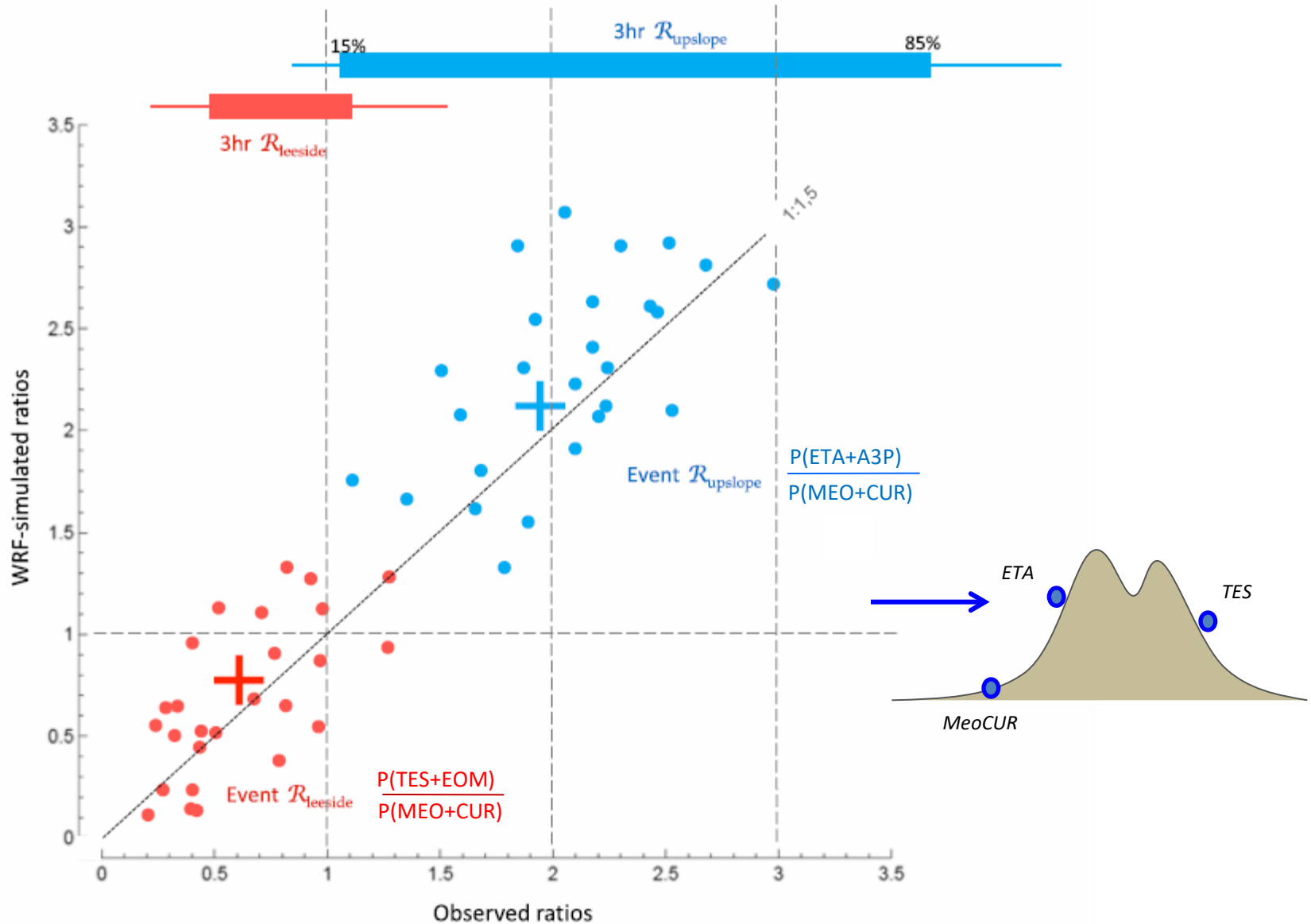
WRF (1 km) continuous run during winter 2011 (May-Sep) forced by GFS

Several weeks of computation in high performance computer...and a lot of pain.

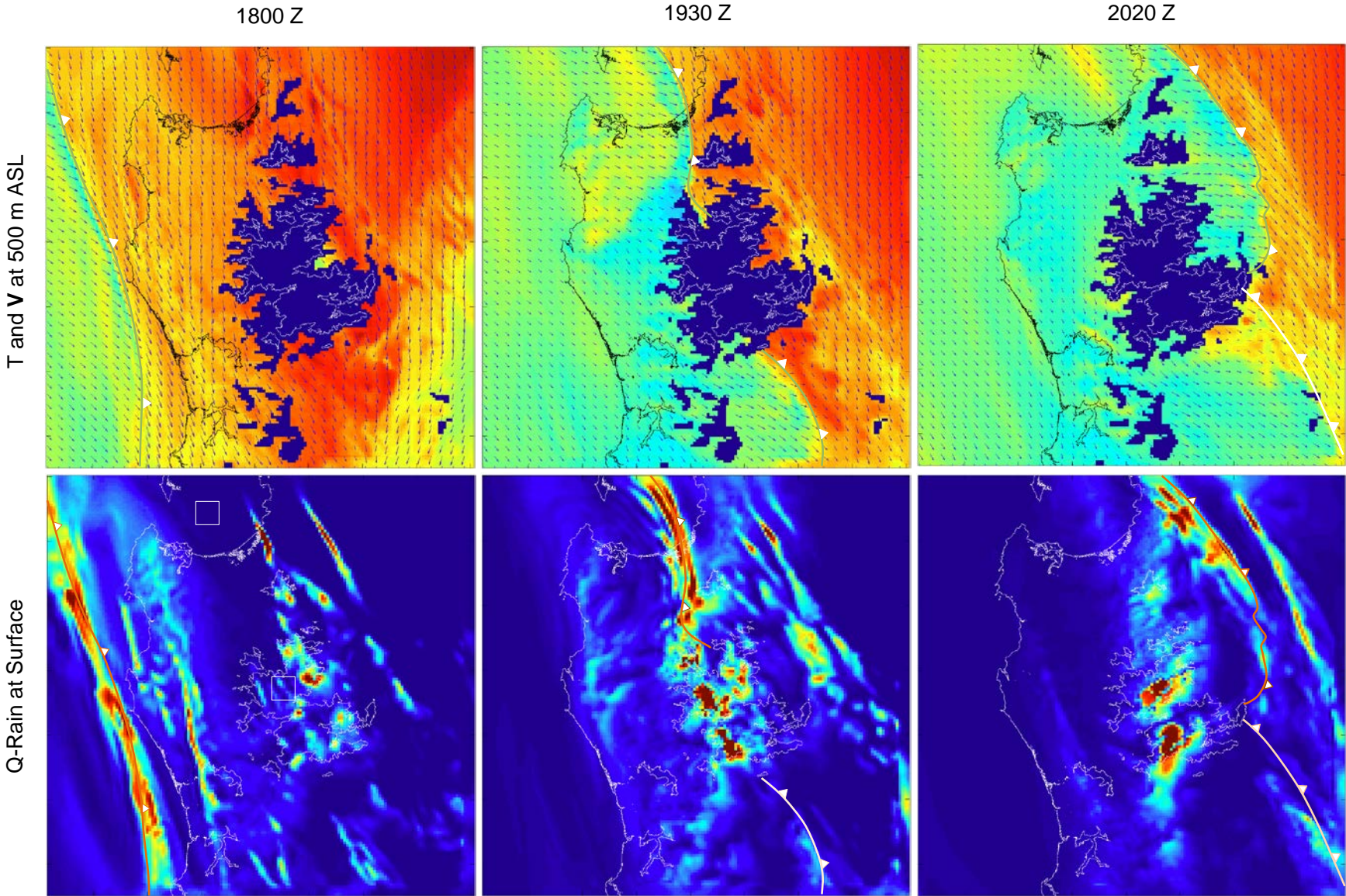


Orographic modification ratios

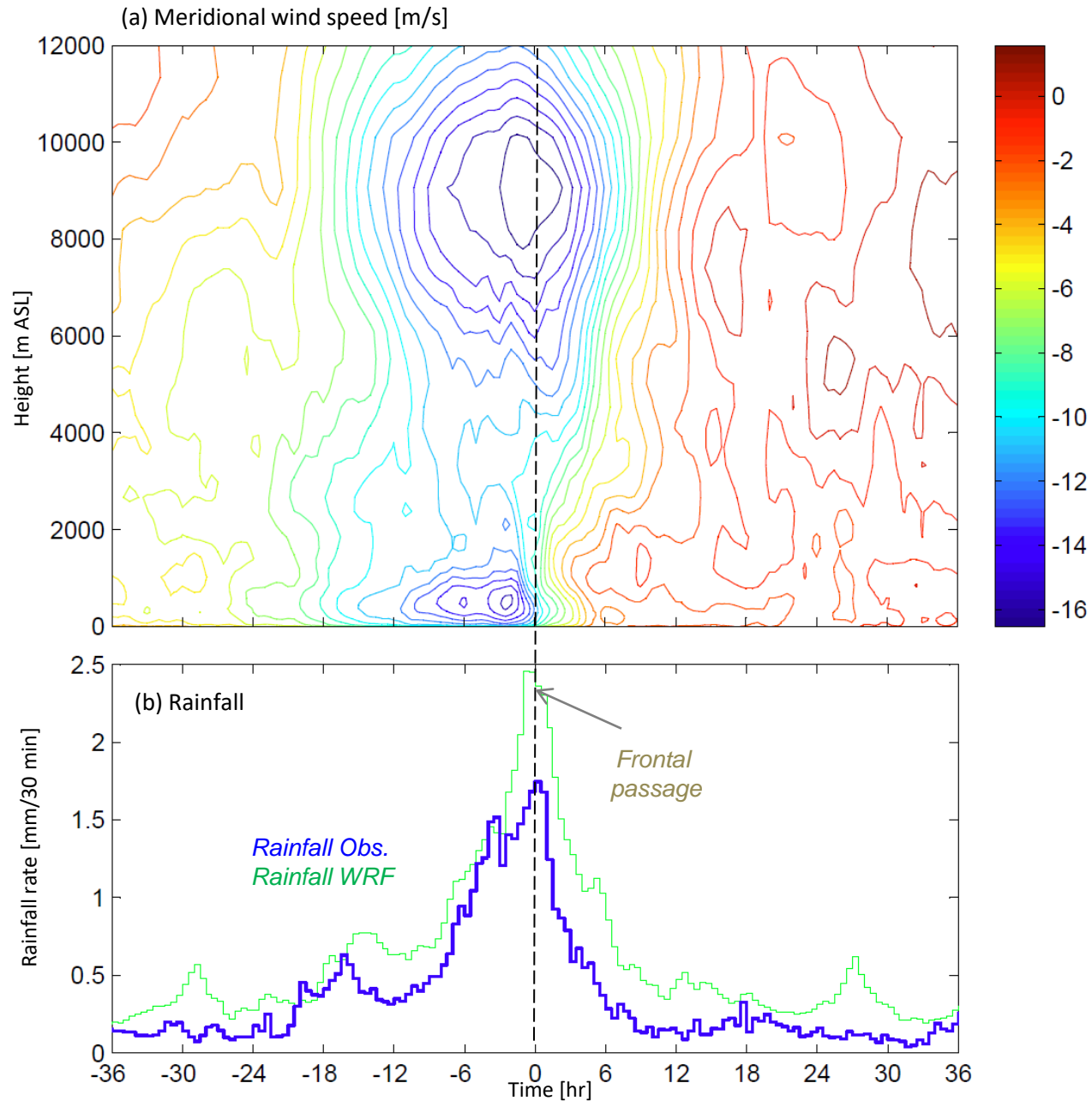
For each of the 27 events....



A typical frontal passage over Nahuelbuta (WRF1km)



Composite frontal passage over Nahuelbuta



Conclusions I: Multi-storm statistics (28 frontal cases)

Parameter	Prefrontal stage	Frontal stage	Postfrontal stage	Annual mean
Duration (hr)	17±5	3	10±6	
Foothill accumulation (%)	45±9	28±9	27±9	
Foothill rain rate (mm/hr)	1.2±0.7	4.7±1	0.5±0.4	
Mnt. rain rate (mm/hr)	2.2±0.8	6.9±1.2	1.6±0.5	
Leeside rain rate (mm/hr)	0.5±0.3	3.6±0.7	0.3±0.3	
Upslope enhancement	5.1±0.4	1.4±0.5	5.5±0.9	1.9
Lee side suppression	0.3±0.2	0.8±0.5	0.5±0.3	0.7

- Metrics of upslope enhancement and lee-side suppression vary widely within the storms (and also between storms)
- Annual mean values can be deceptive

Modelo básico de precipitación sobre una pendiente (Raw upslope model, e.g., Smith 1979)

Tasa de condensación:

$$\frac{D\rho_{w/sat}}{Dt} = w \frac{d\rho_{w/sat}}{dz}$$

Si los hidrometeoros caen al suelo de manera instantánea

$$R \left(\frac{kg}{m^2seg} \right) = \int_0^\infty w(z) \frac{d\rho_{w/sat}}{dz} dz$$

Caso simple: $w(z) = \alpha U(z)$

$$R = \alpha \int_0^\infty U(z) \frac{d\rho_{w/sat}}{dz} dz$$

Supongamos $U(z)=\text{constante}$ y $\alpha = \frac{dh}{dx}$ (pendiente del terreno)

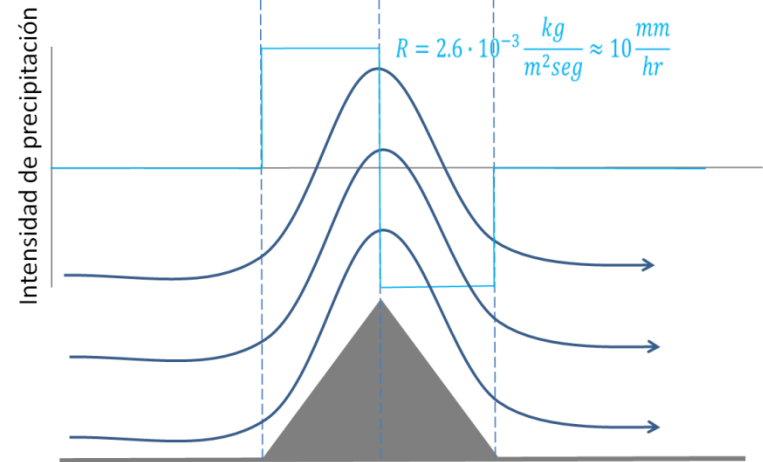
$$R = \alpha U [\rho_{w/sat}]_0^\infty$$

Lo cual se reduce a

$$R = U \frac{\partial h}{\partial x} r_{sat}(z=0) \rho_{aire}(z=0)$$

$$L = 1 \text{ km}, 2L = 100 \text{ km}, \alpha = \frac{1}{50}, U = 10 \text{ ms}^{-1}$$

$$r = 15C, r_{sat} = 11 \frac{g}{kg}, \rho_{aire} = 1.2 \text{ kg/m}^3$$

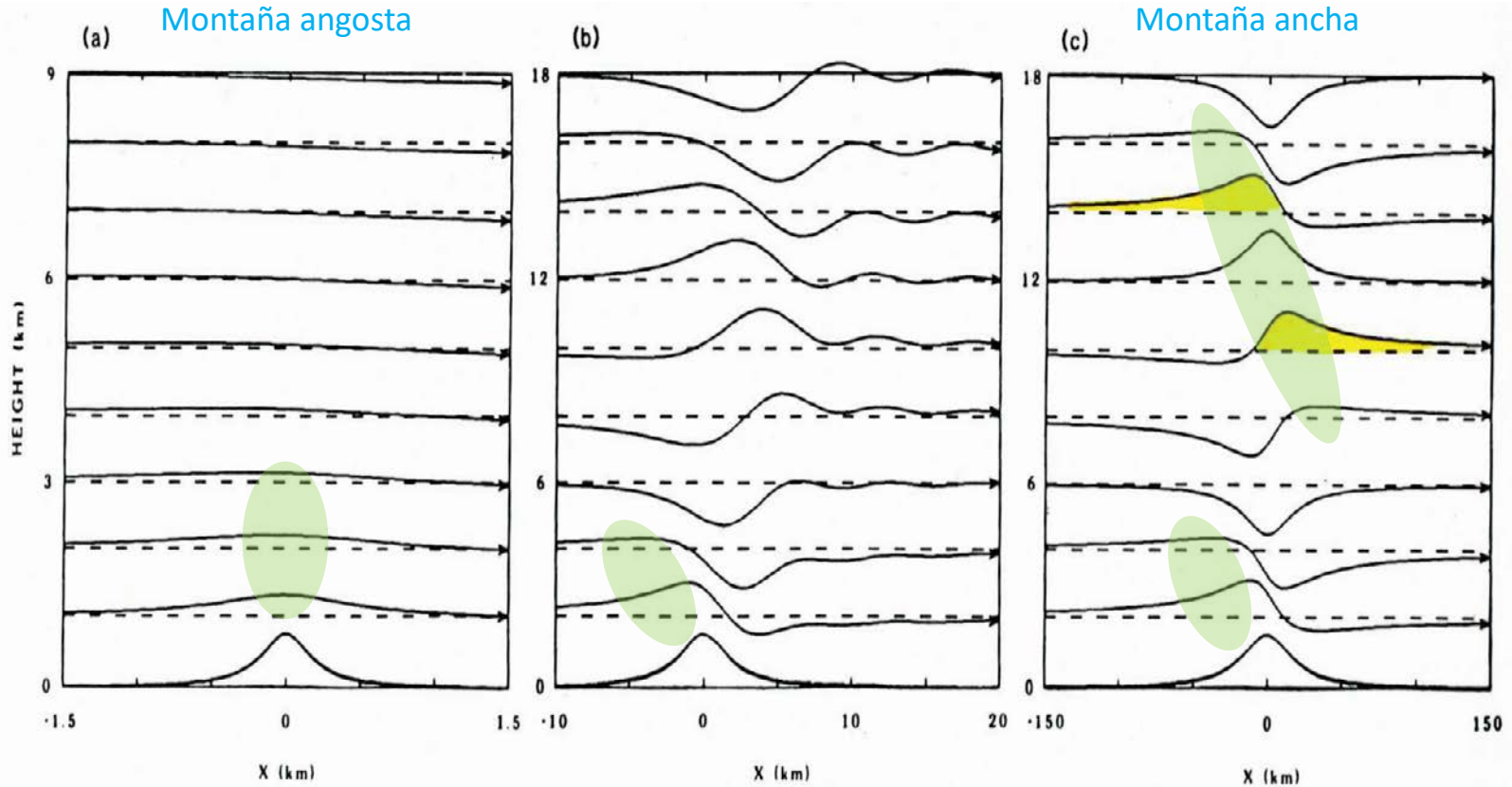


Demasiada precipitación!....Demasiado simple!

Faltan dos efectos importantes: Dinámica del flujo sobre la montaña y microfísica

Ondas de gravedad generadas por topografía

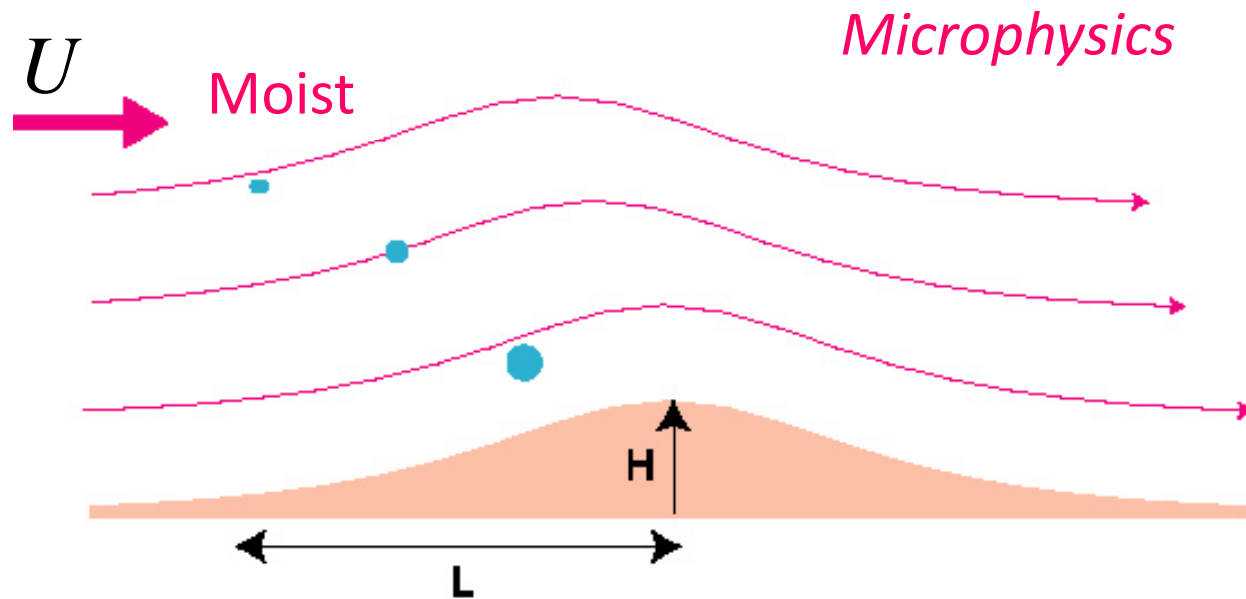
Caso de una montaña aislada. Notar ascenso corriente arriba de la montaña



$$Z_{\text{penetración}} \approx a$$

$$Z_{\text{penetración}} \approx \frac{U}{N}$$

En caso de un ambiente saturado se debe sustituir $N(\sim 0.01\text{s}^{-1})$ por $N_{\text{moist}}(\sim 0.005\text{s}^{-1})$



$$\tau_{microphysics} \approx 1000s$$

$$\tau_{airflow} \approx L/U$$

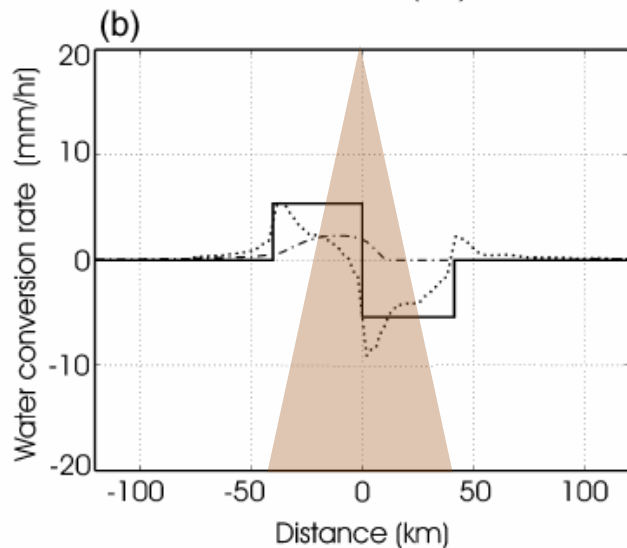
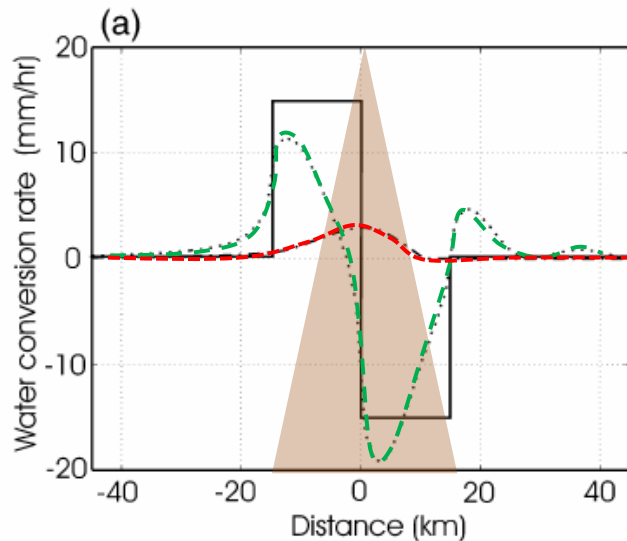
$$Si \quad U \approx 10m/s \quad y \quad L = 100km \quad \tau_{airflow} \approx 10.000seg$$

$$Si \quad U \approx 10m/s \quad y \quad L = 10km \quad \tau_{airflow} \approx 1.000seg$$

A Linear Theory of Orographic Precipitation

RONALD B. SMITH AND IDAR BARSTAD

Department of Geology and Geophysics, Yale University, New Haven, Connecticut



$$\frac{Dq_c}{Dt} \approx \mathbf{U} \cdot \nabla q_c = S(x, y) - \frac{q_c}{\tau_c} \quad (1)$$

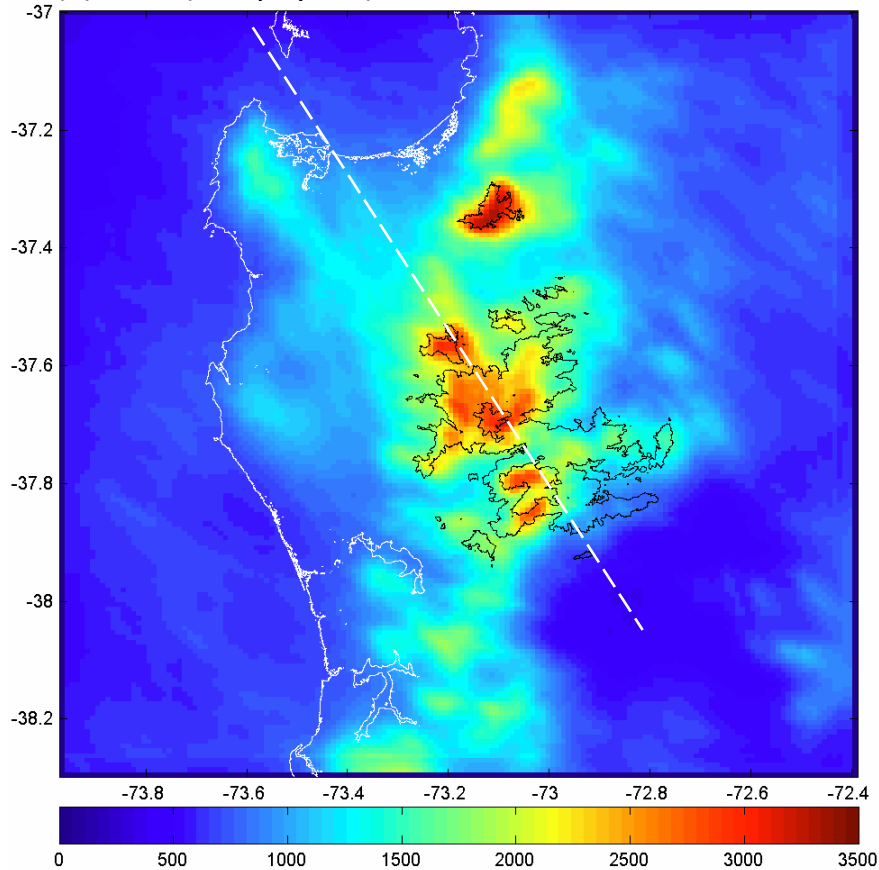
$$\frac{Dq_s}{Dt} \approx \mathbf{U} \cdot \nabla q_s = \frac{q_c}{\tau_c} - \frac{q_s}{\tau_f}, \quad (2)$$

Ondas de gravedad producen ascenso delante y sobre la montaña desplazando zona de precipitación corriente arriba

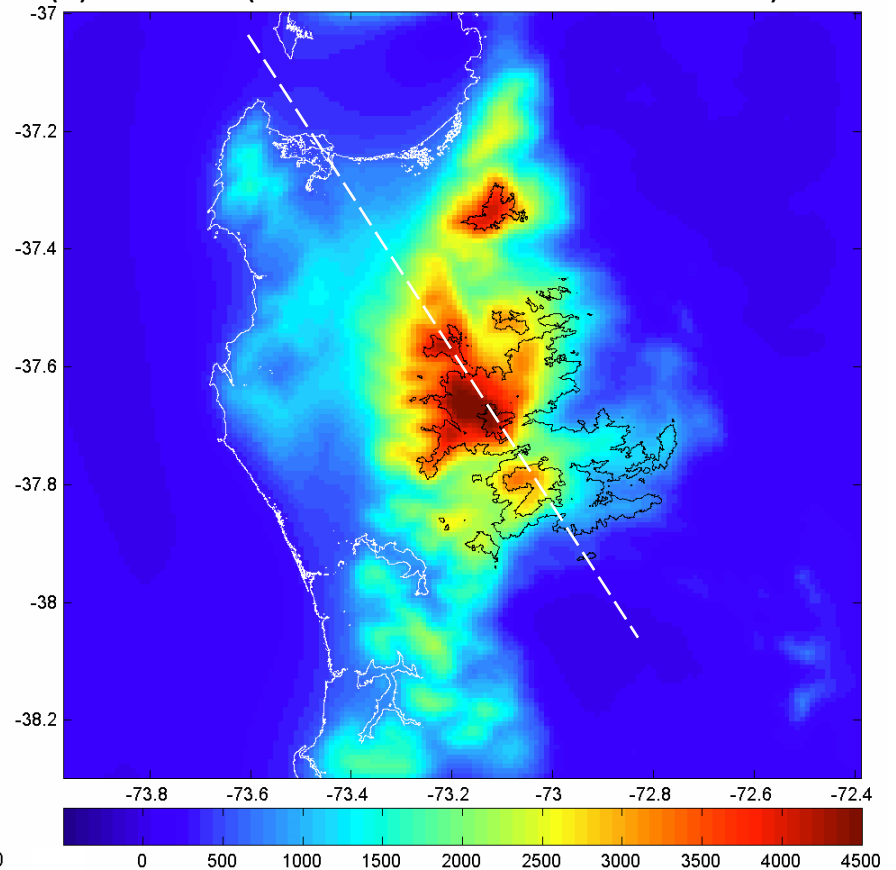
Microfísica reduce tasa de precipitación y desplaza máximo corriente abajo

Simulated 2011 winter (May-Sep) Precipitation [mm]

(a) WRF (Full physics)



(b) LT Model (var. Wind and moisture from WRF)



(*) Linear Theory Model by Smith and Barstad (2004)

$$\tau_c = \tau_f = 1000 \text{ s}, P_\infty = 0$$

30 min of calculation in domestic PC

How similar are WRF and LT precipitation pattern at individual events?

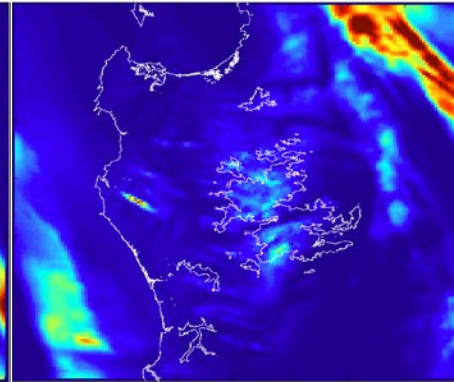
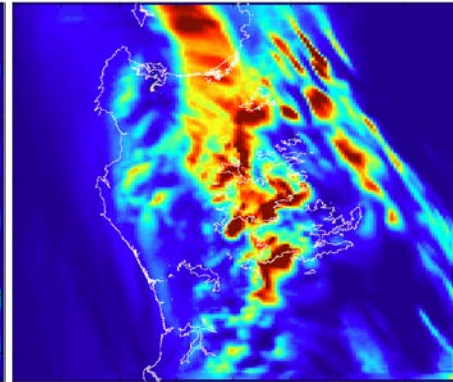
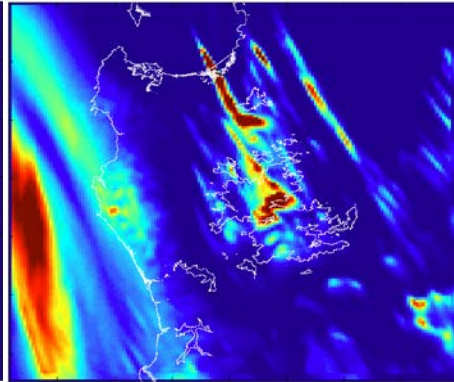
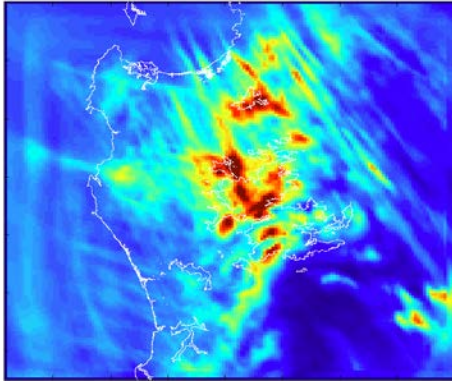
Full event (36 hr)

Prefrontal (20')

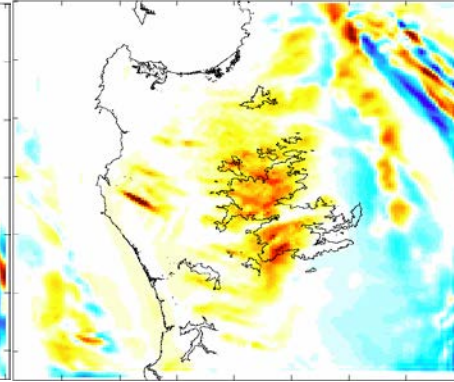
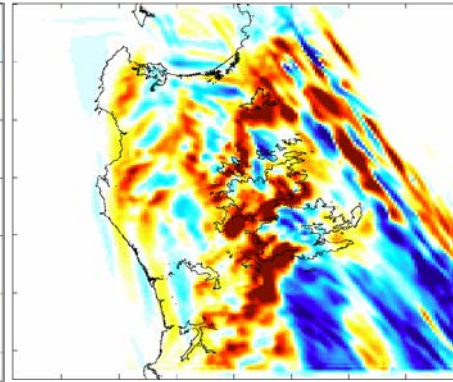
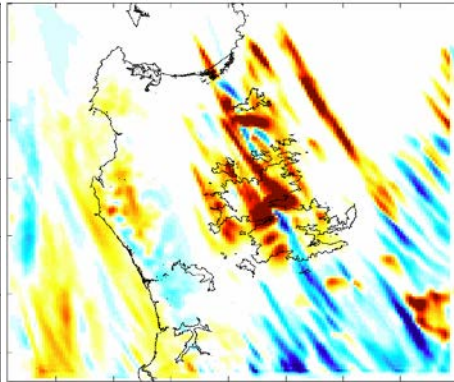
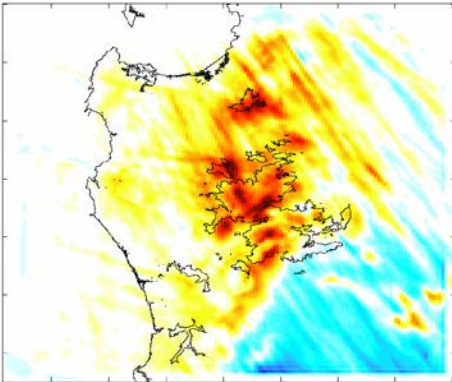
Frontal (20')

Postfrontal (20')

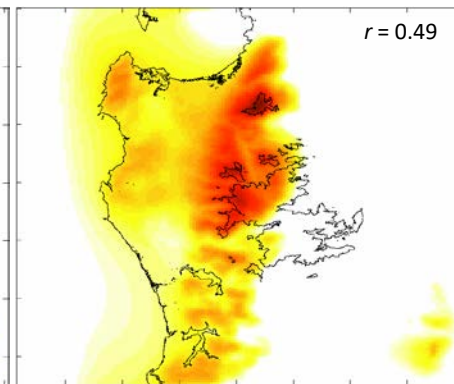
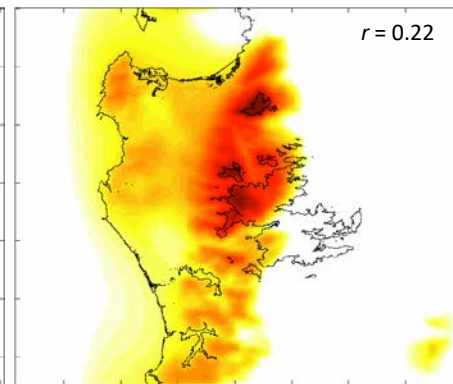
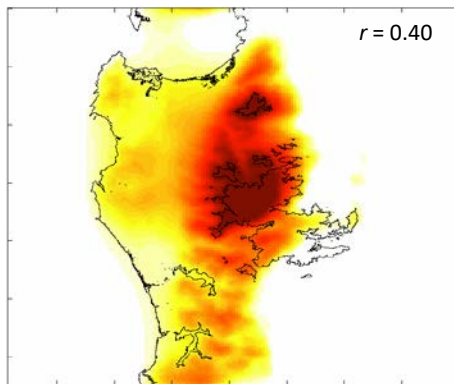
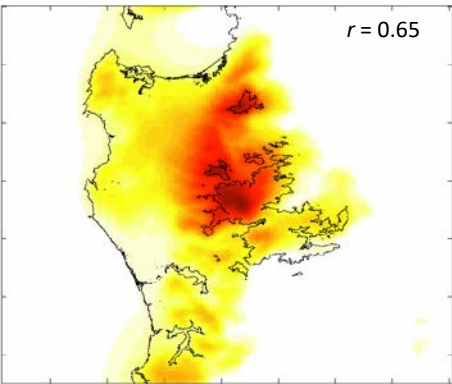
Full WRF



Oro. WRF

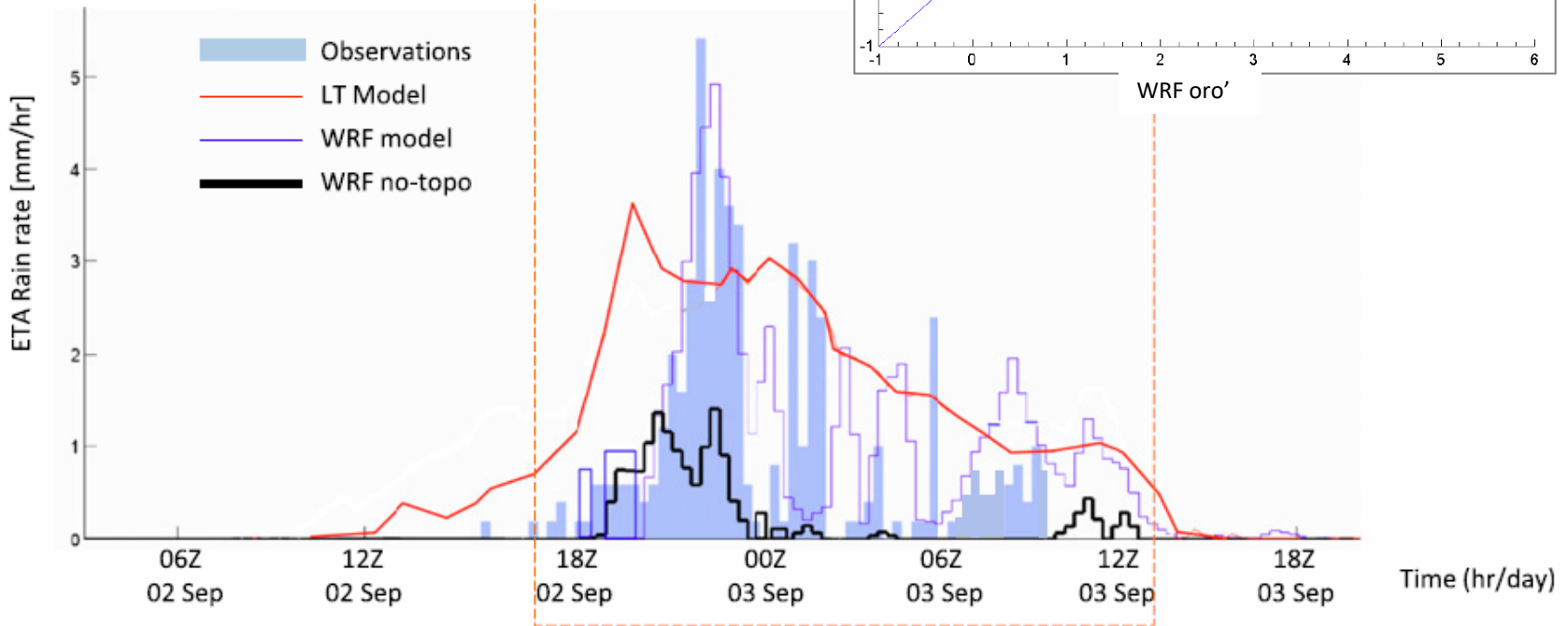
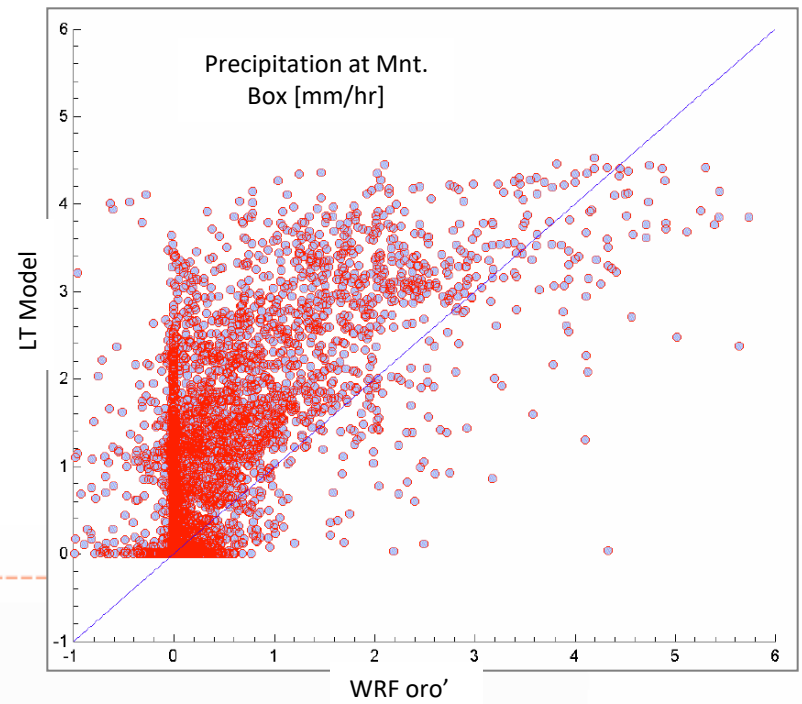


LT Model



Orographic WRF: Full topo – No topo

How similar are the WRF and LT-Model precipitation pattern at individual events?

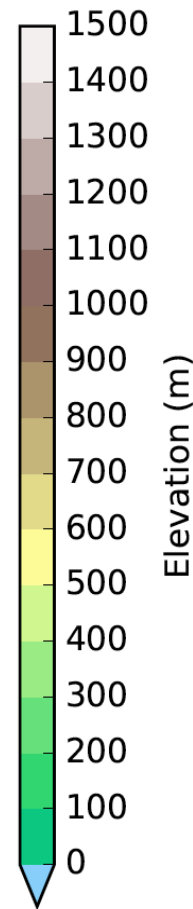
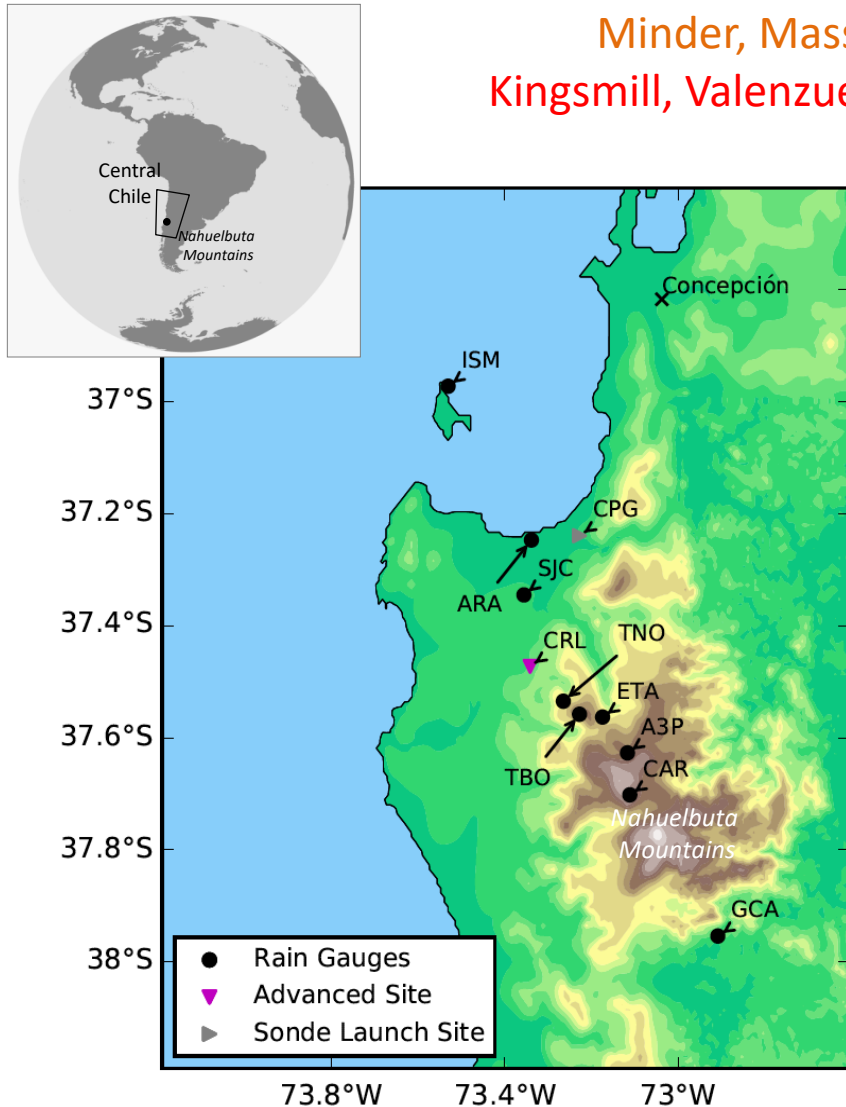


Conclusions I

- ✓ WRF model does a good job in simulating the seasonal mean and event rainfall accumulation. WRF itself partially linear.
- ✓ Linear model does capture the seasonal rainfall distribution of precipitation over the Nahuelbuta mountains, although it overestimate accumulation in the windward side and produce a too strong rain shadow effect.
- ✗ Over/under estimations in the LT model can be reduced by tuning their parameters and filtering out many periods of light precipitation that the model produce before actual rainfall began.
- ✗ LT model can't resolve intense, short-lived (less than an hour) rainfall episodes that are associated with non-linear effects during frontal passage. This episodes are highly variable in time and space, so they smooth when considering daily or longer periods.

The Chilean Coastal Orographic Precipitation Experiment Pilot Project (CCOPE-2015)

Minder, Massman; Geerts, Fults, Sneider;
Kingsmill, Valenzuela; Garraud, Falvey, Montecinos



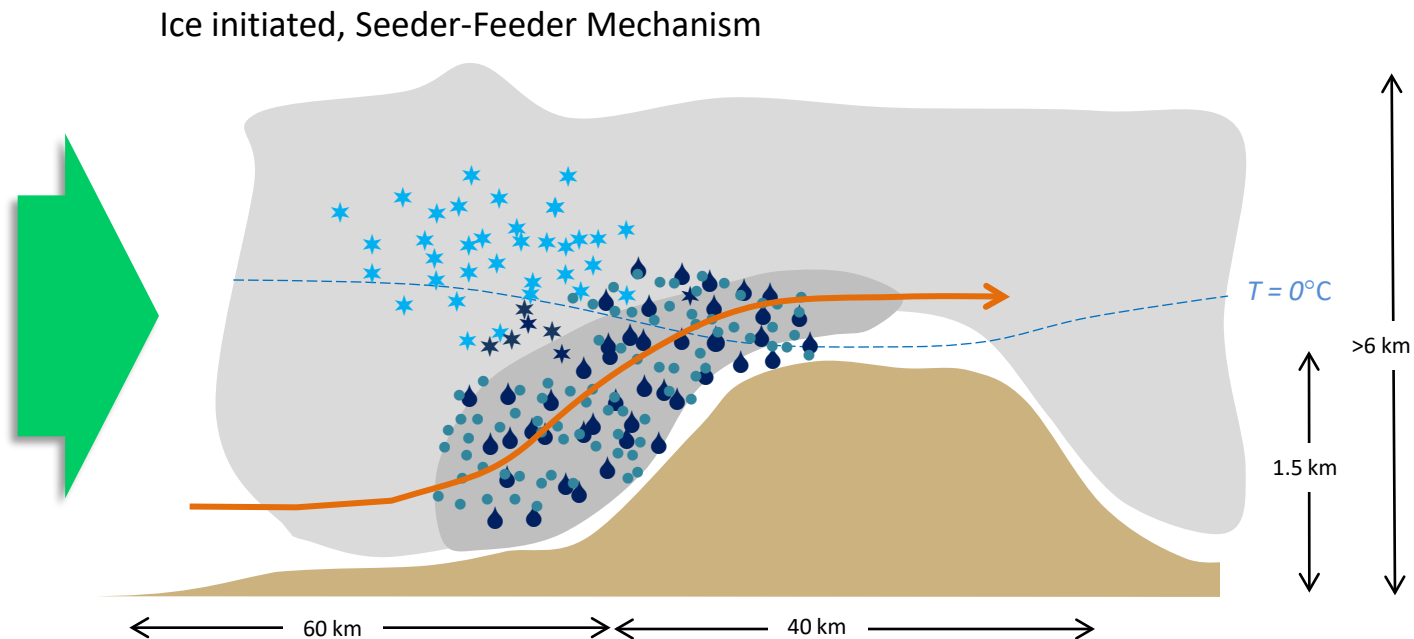
Precipitación Orográfica depende de:

Estabilidad del flujo ($Fr=U/Nh$)

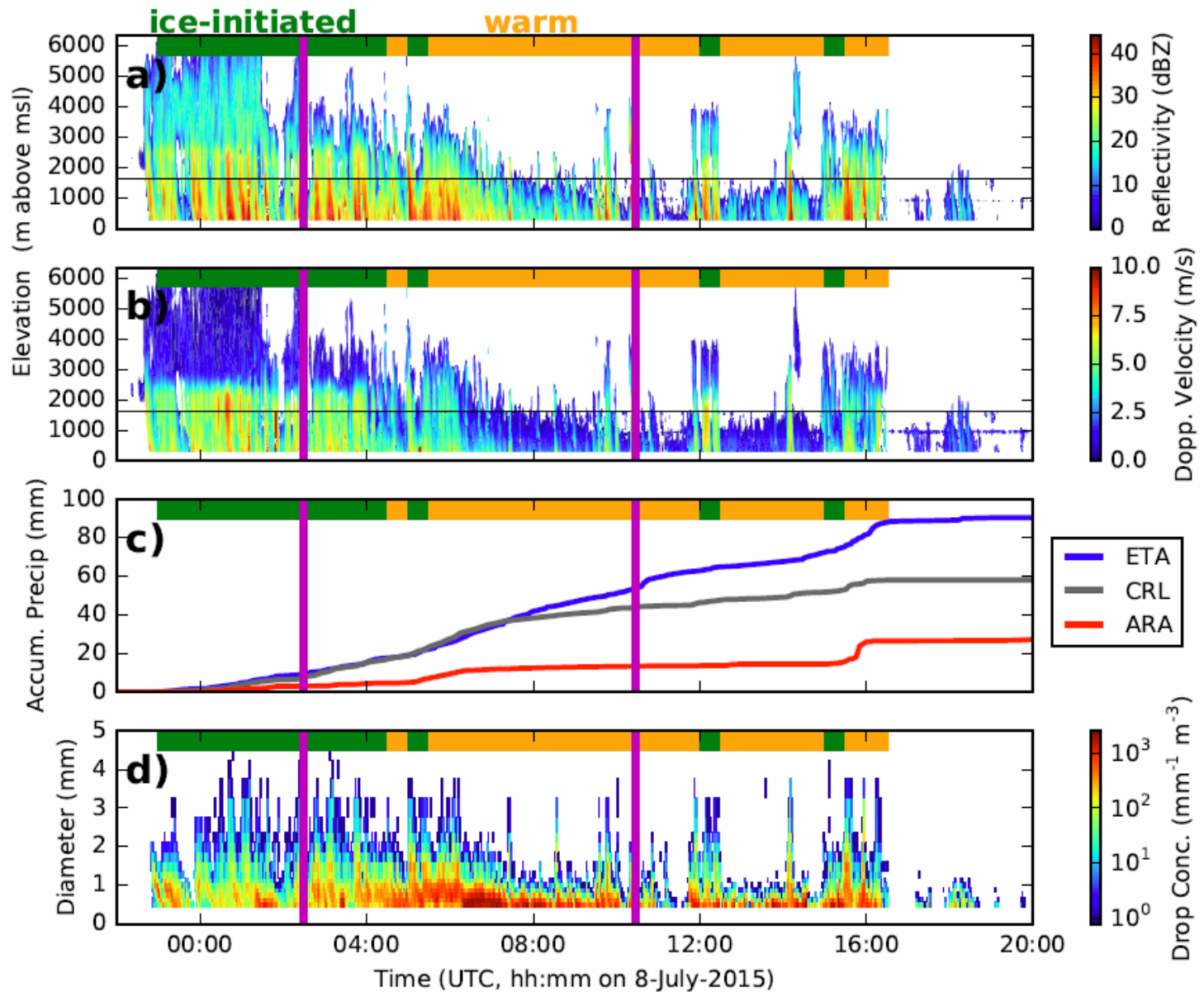
Estabilidad termodinámica (convección?)

Contenido de humedad (IWV)

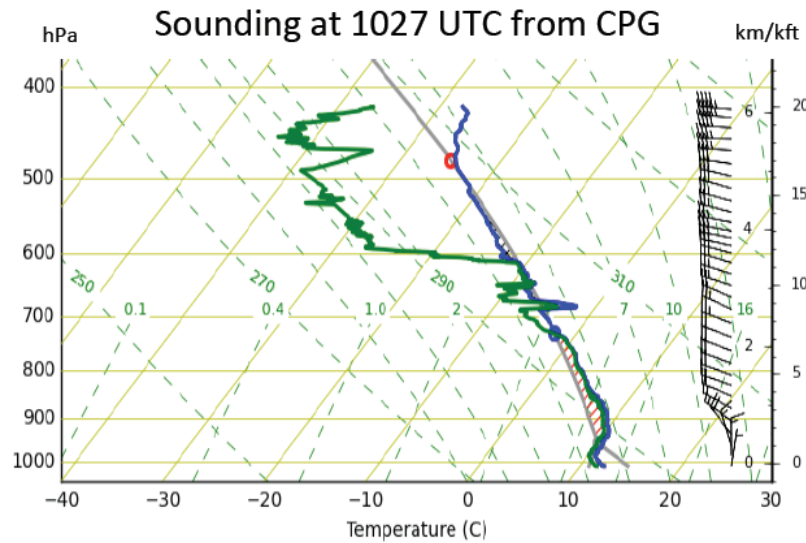
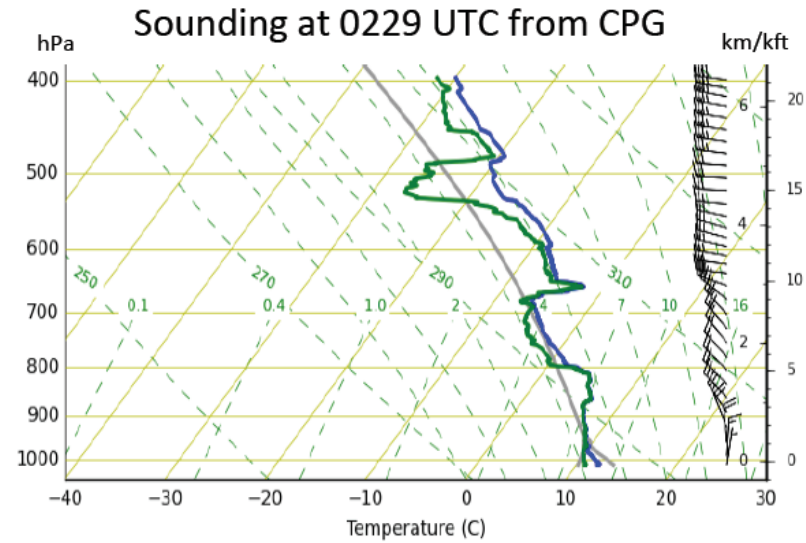
Microfísica ($\tau_{\text{rain}} < \tau_{\text{adv}} = L/U$)



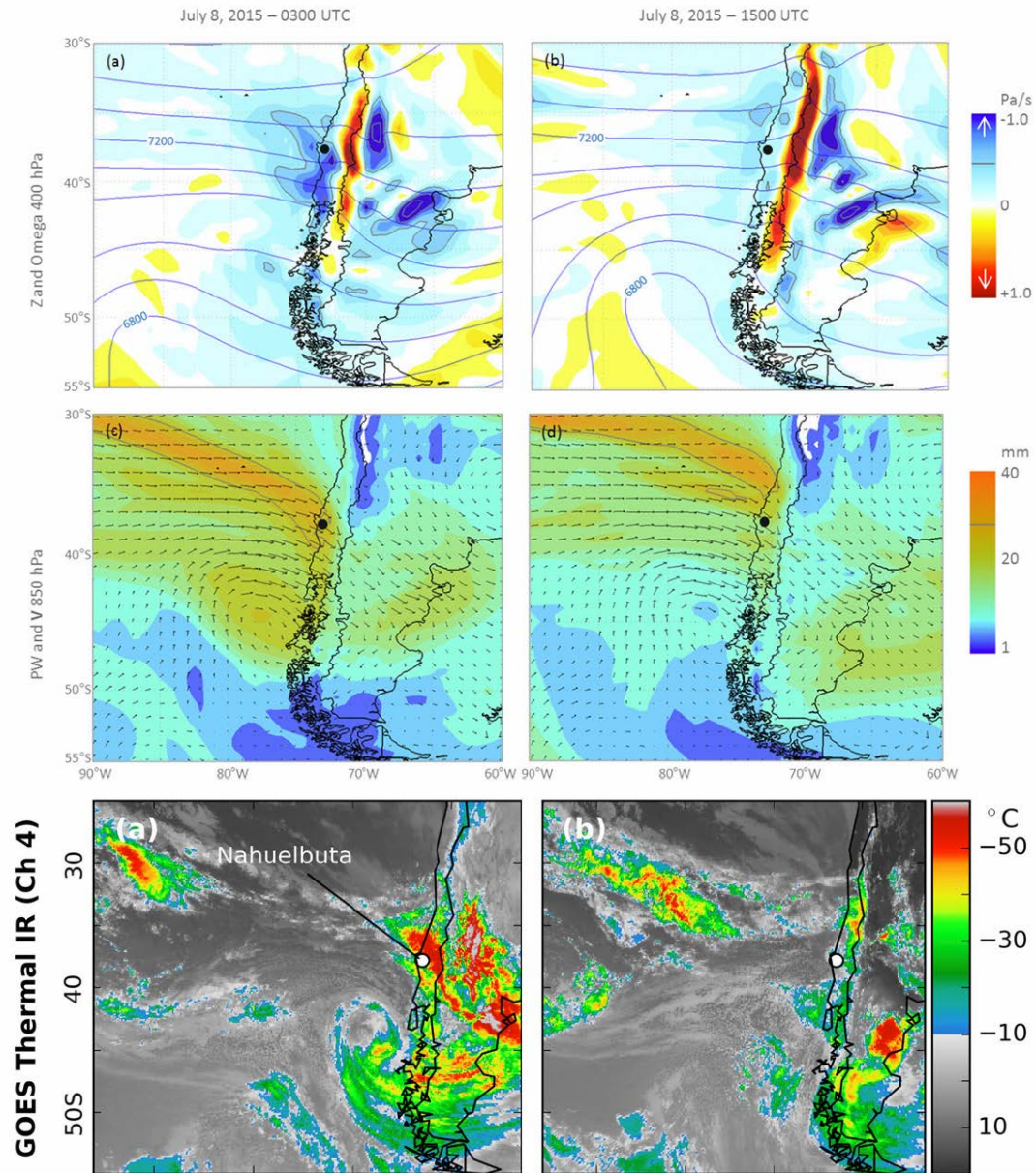
...y aquí viene una sorpresa!



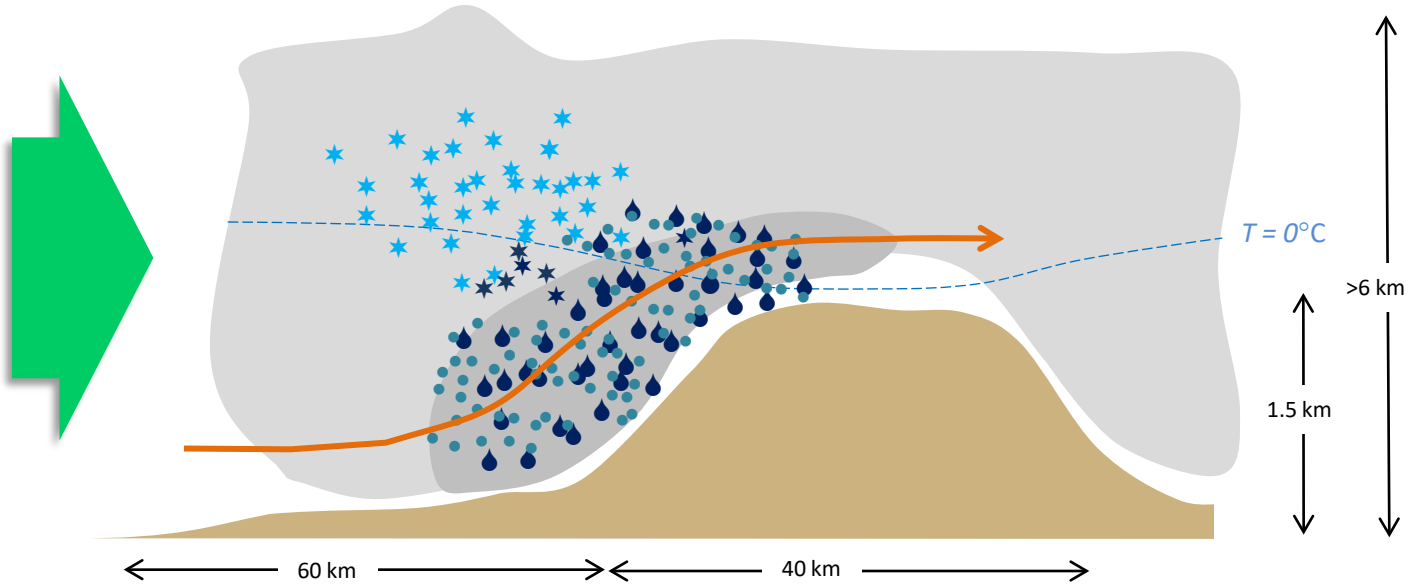
...y aquí viene una sorpresa!



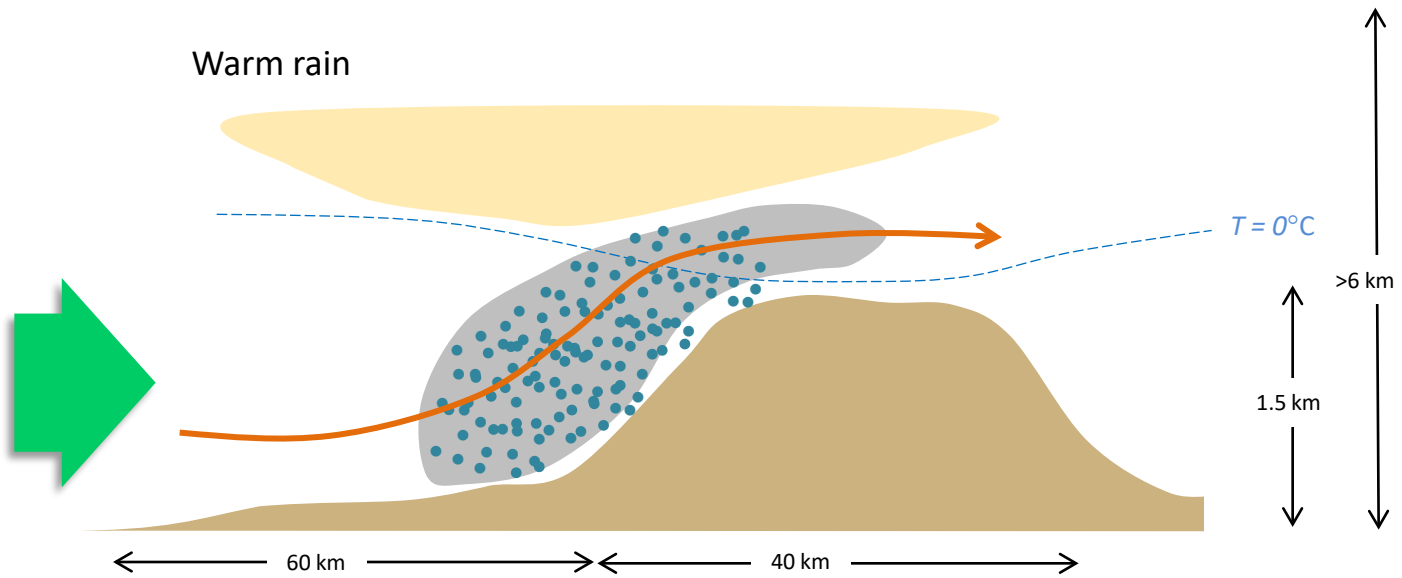
Transition from ice-initiated to warm rain controlled by synoptic evolution



Ice initiated, Seeder-Feeder Mechanism

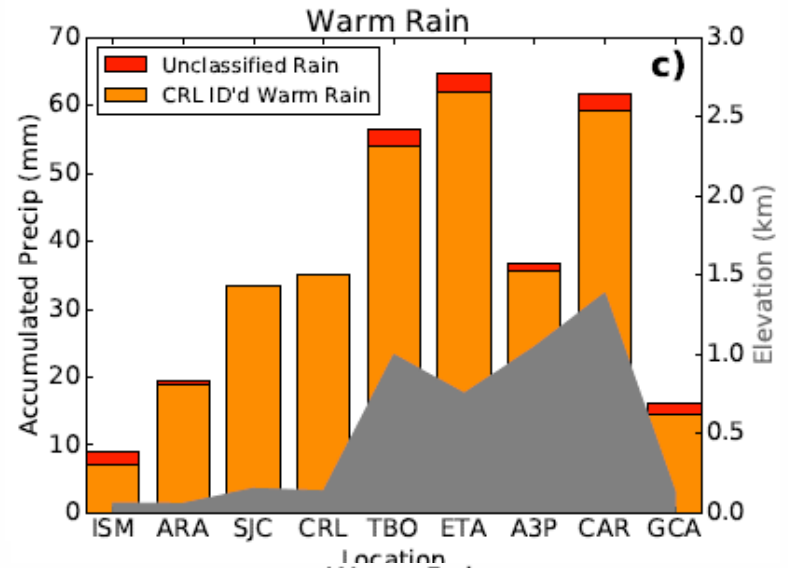
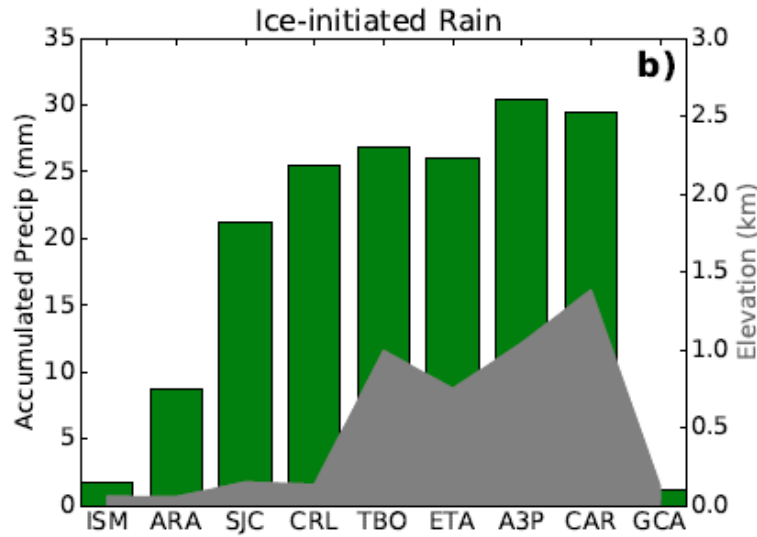


Warm rain

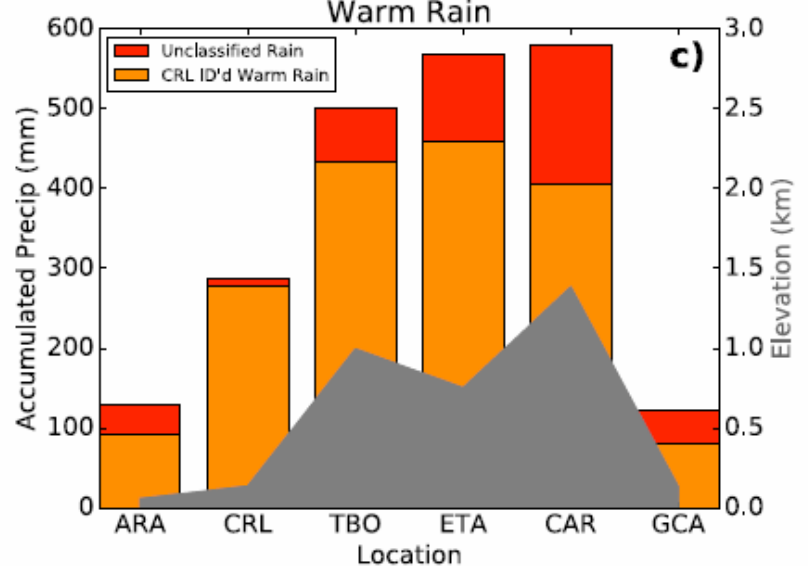
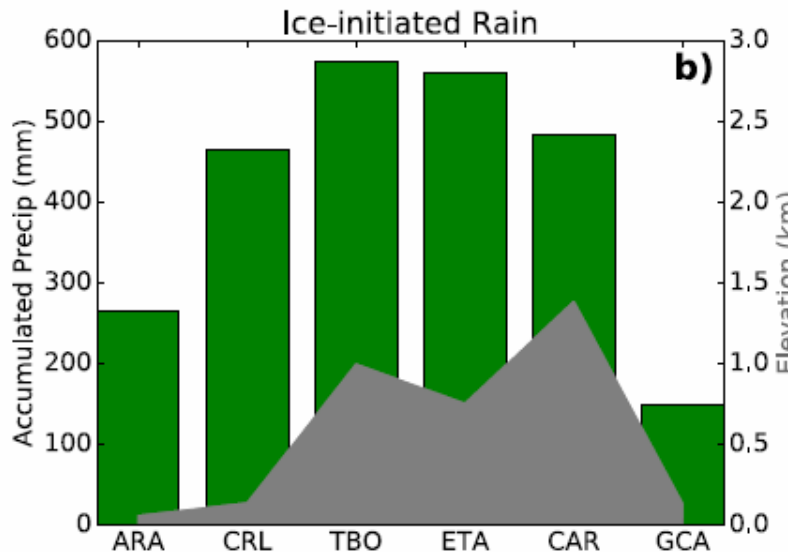


Impacto de regimen de precipitación en GOP

Evento
8-Jul



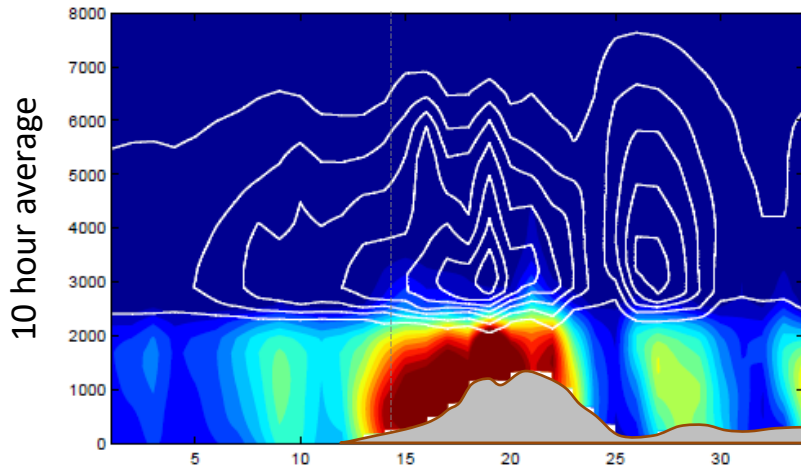
Todos



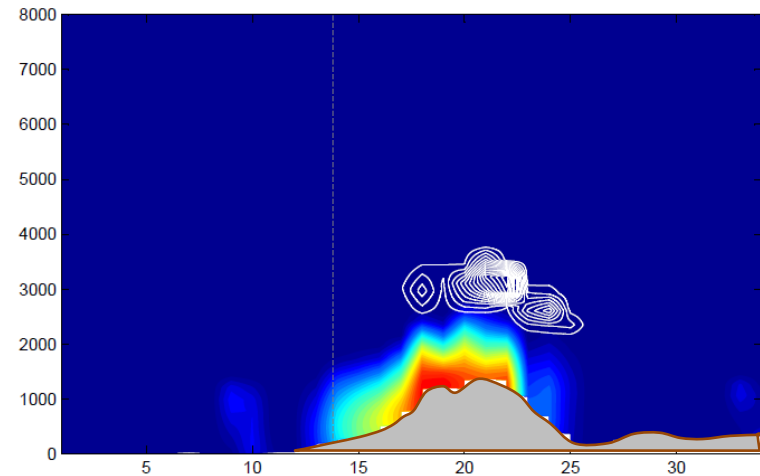
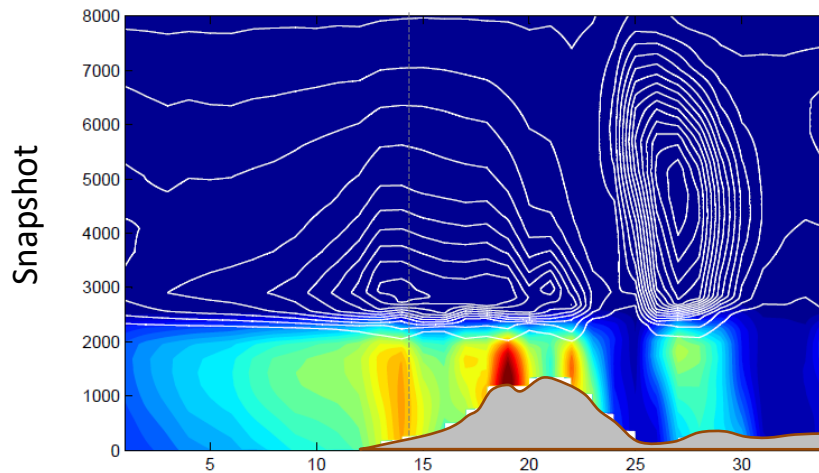
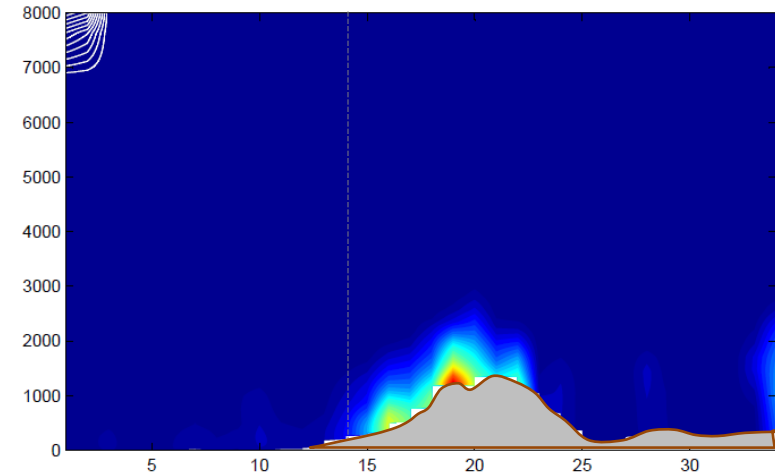
AFEX WRF simulation

High-distance cross-section (NW-SE) of q_{rain} and q_{frozen}

Ice initiated rain period



Warm rain period

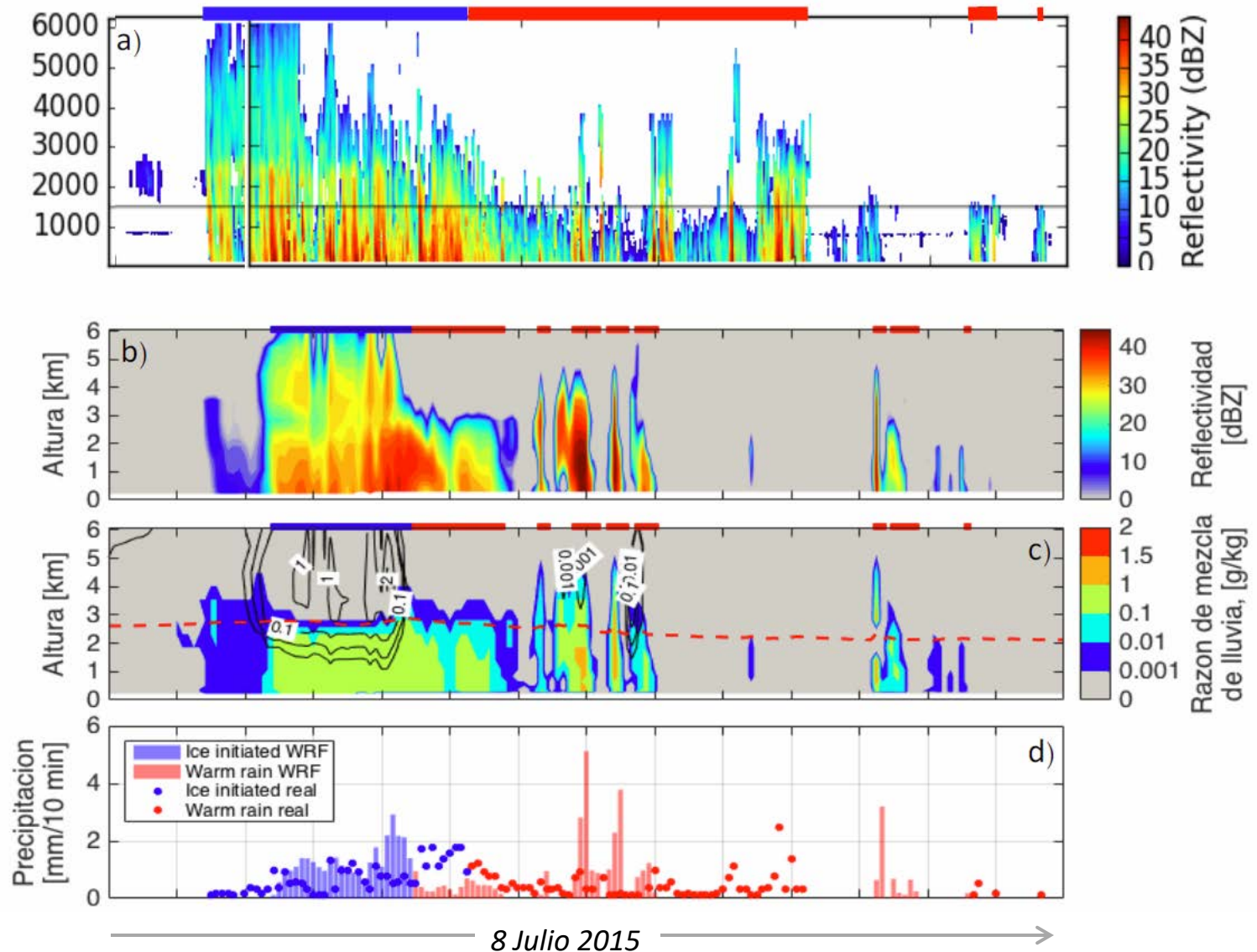


← 180 km →

← 180 km →

Podemos emplear WRF para estudiar esto? Si!

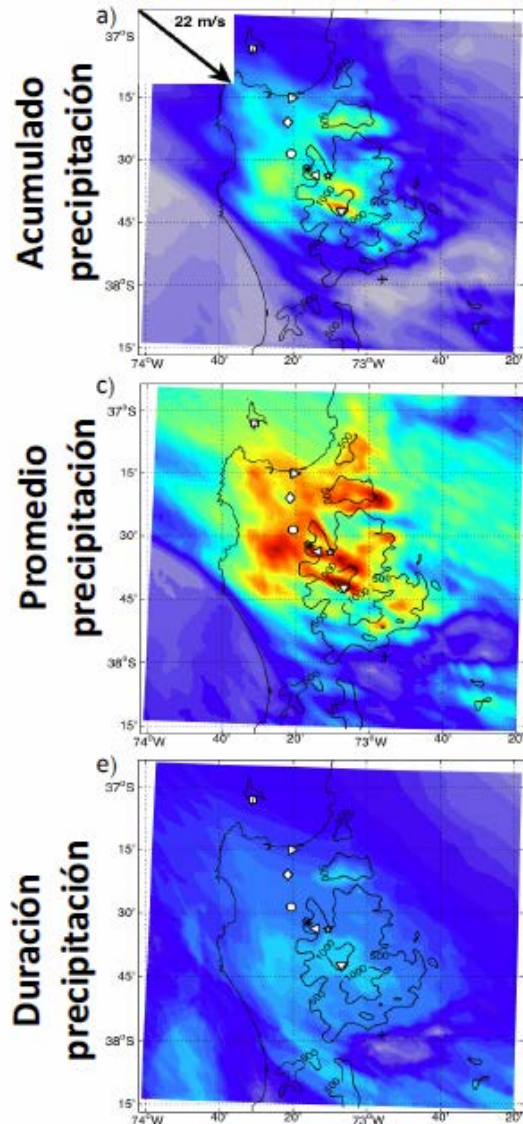
Poster/Tesis(MMC) Cinthya Bravo, DMC



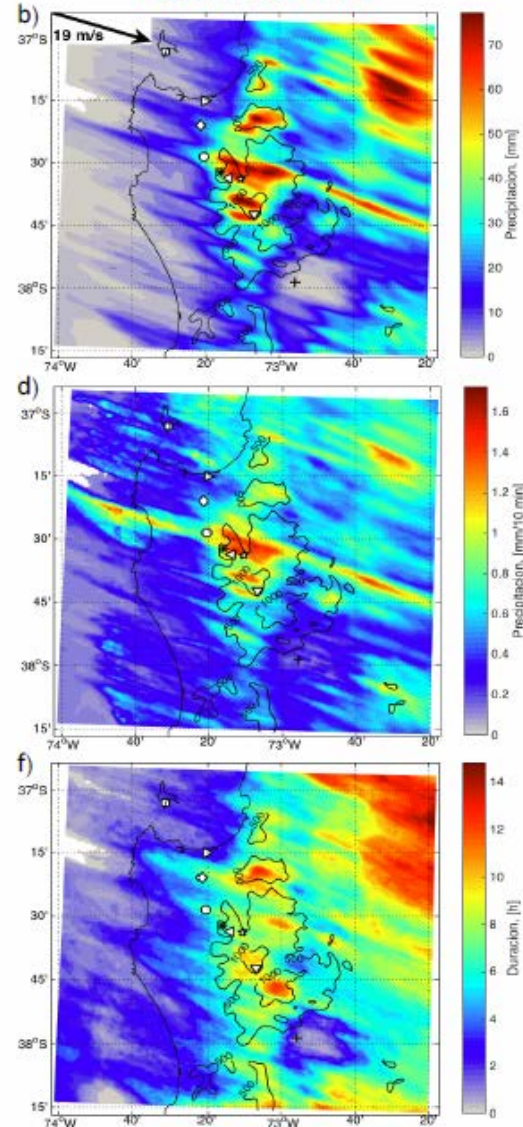
Podemos emplear WRF para estudiar esto? Si!

Poster/Tesis(MMC) Cinthya Bravo, DMC

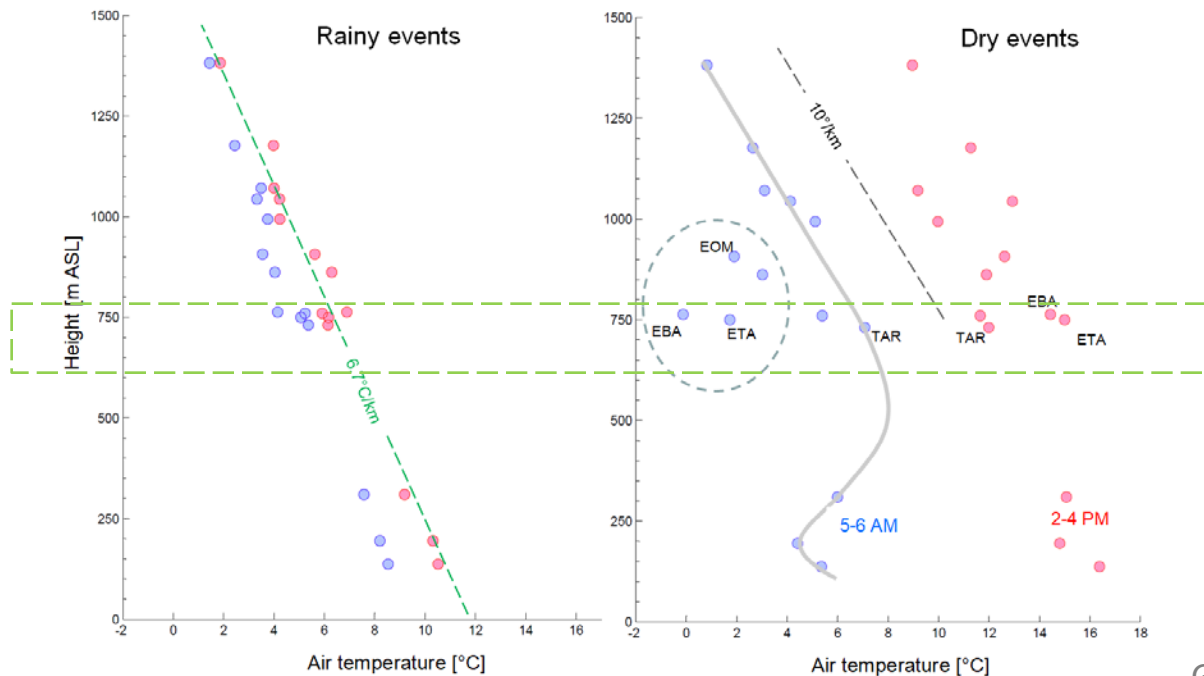
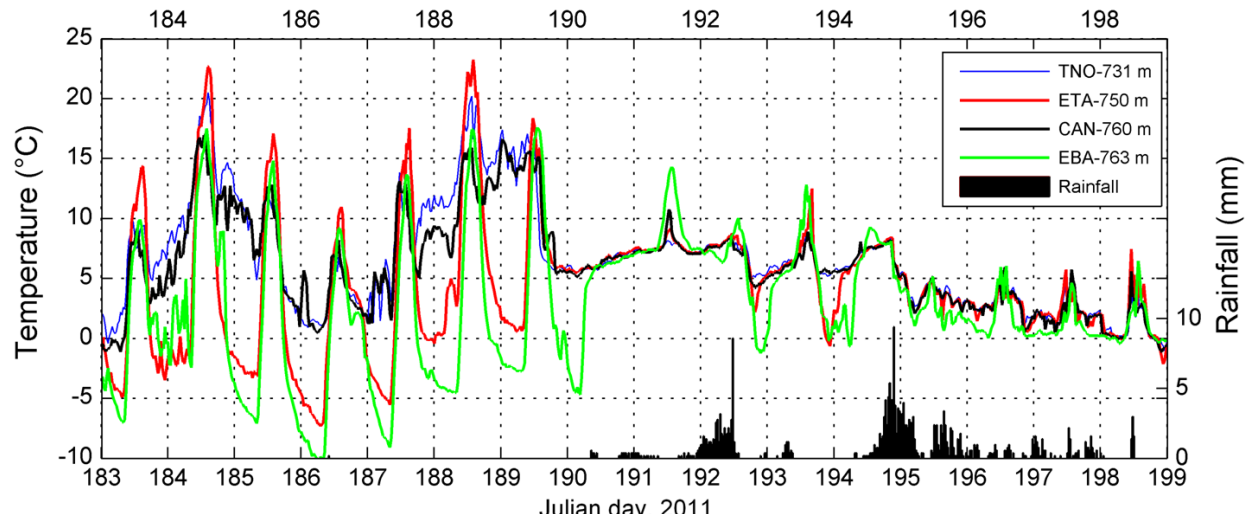
Lluvia iniciada por hielo



Lluvia cálida



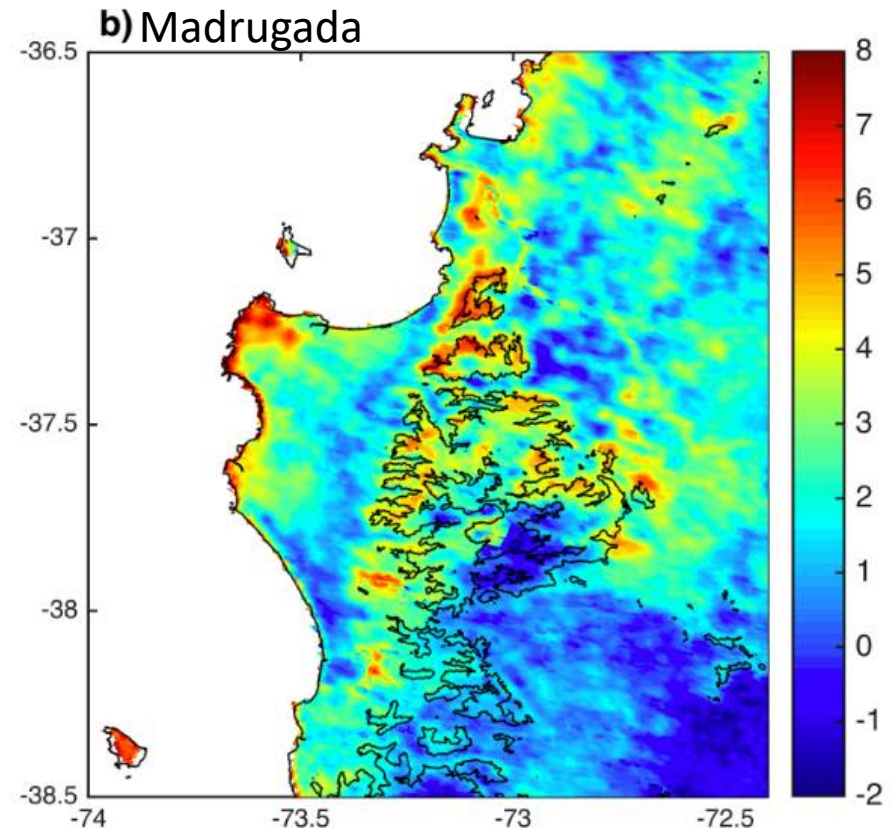
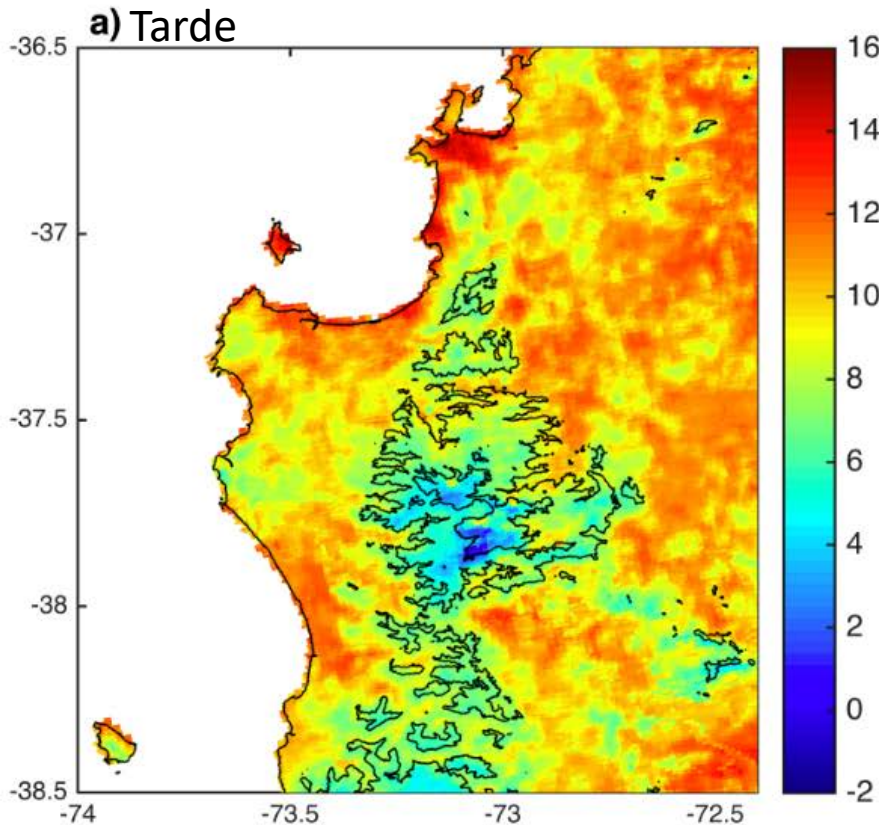
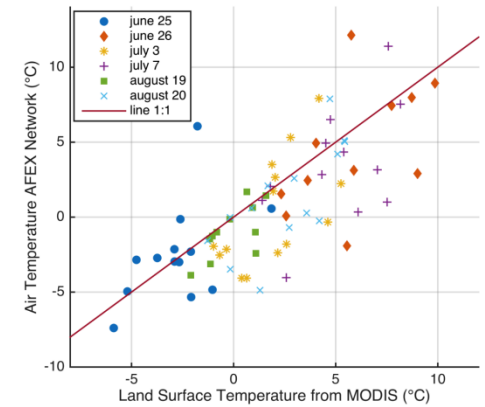
Campo de temperatura sobre Nahuelbuta: T(z)



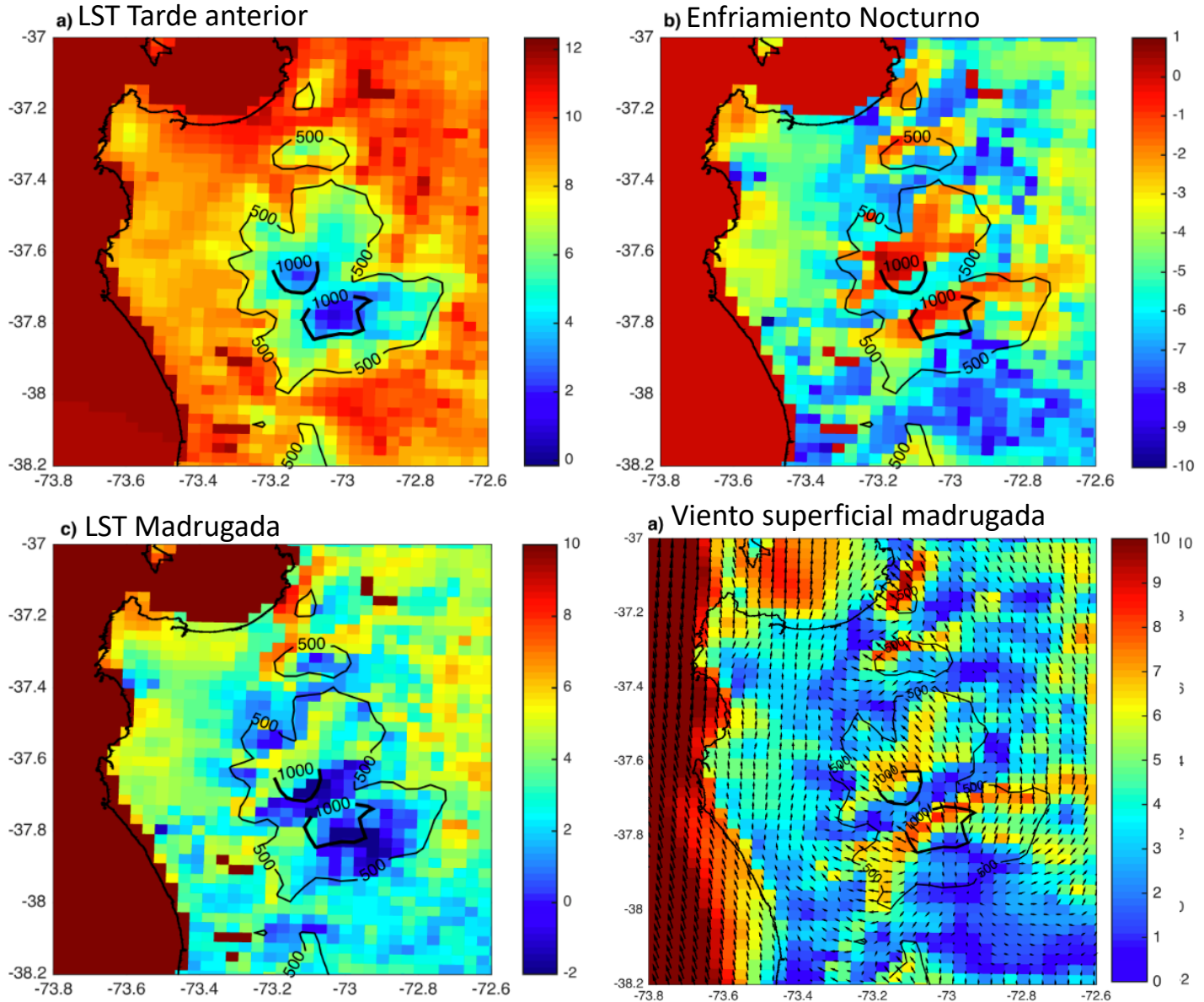
MODIS Land Surface Temperature

2xdía, 250 m, 2001-hoy

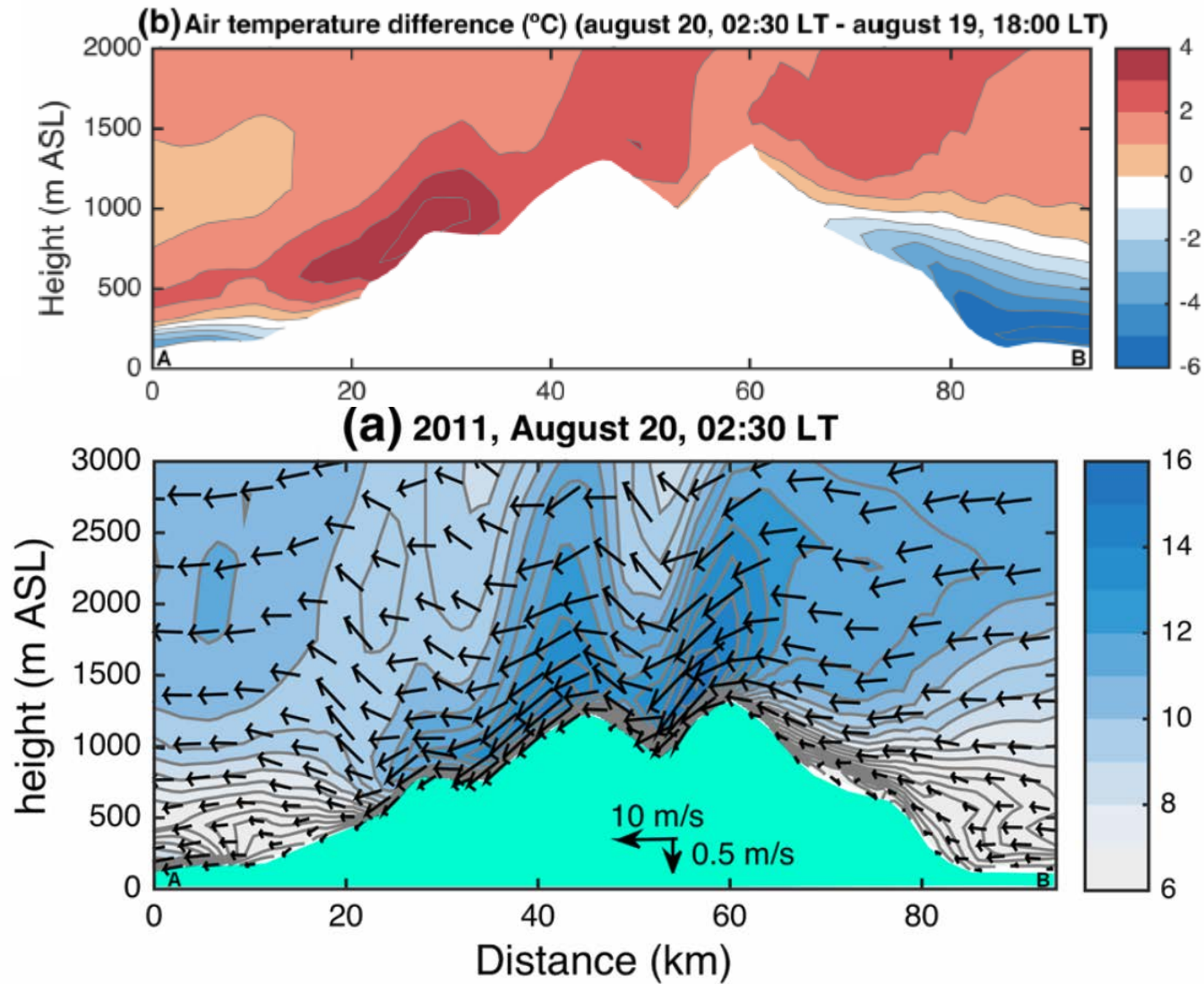
Compuesto LST pada días despejados 2011



Simulación WRF 3km caso 21 Agosto 2011



Simulación WRF 3km caso 21 Agosto 2011



Conclusiones III

- Durante el día es razonable emplear un gradiente adiabático para determinar $T(z)$
- En presencia de precipitación (o al menos nubosidad) es razonable emplear el gradiente adiabático saturado
- Durante noches despejadas, el campo de temperatura superficial es complejo y modulado por la acción del viento tanto en superficie como por la formación de ondas de montaña en altura.

<http://dgf.uchile.cl/rene/Nahuelbuta/>

Publicaciones

Garreaud, R., M. Falvey and A. Montecinos: Orographic precipitation in coastal southern Chile, 2016: Mean distribution, temporal variability and linear contribution. *Journal of Hydrometeorology*, **17**, 1185-1202

González, S. and R. Garreaud, 2017: Spatial variability of near-surface temperature over the coastal Mountains in southern Chile (38°S). *Meteorol. Atmos. Phys.* <https://doi.org/10.1007/s00703-017-0555-4>.

Massmann, A., J. Minder, R. Garreaud, D. Kingsmill, R. Valenzuela, A. Montecinos, S. Fuels and J. Snider, 2017: The Chilean Coastal Orographic Precipitation Experiment: Observing the influence of microphysical rain regime on coastal orographic precipitation. *Journal of Hydrometeorology*, **18**, 2723-2743.

Hobouchian, M.P., P. Salio, Y. García-Skabar, D. Vila, R. Garreaud, 2017: Assessment of satellite precipitation estimates over the slopes of the subtropical Andes. *Atmospheric Research*, **190**, 43–54

Fuels, S., Massmann, A. Montecinos, E. Andrews, D. Kingsmill, J. Minder, R. Garreaud, J. Snider, 2018: Wintertime Aerosol Measurements during the Central Chilean Orographic Precipitation Experiment

Tesis

Cristian Muñoz, 2014: Rol de la orografía costera en la precipitación de Chile central. [Magister en Meteorología y Clima](#). Universidad de Chile. Prof. Guía: R. Garreaud

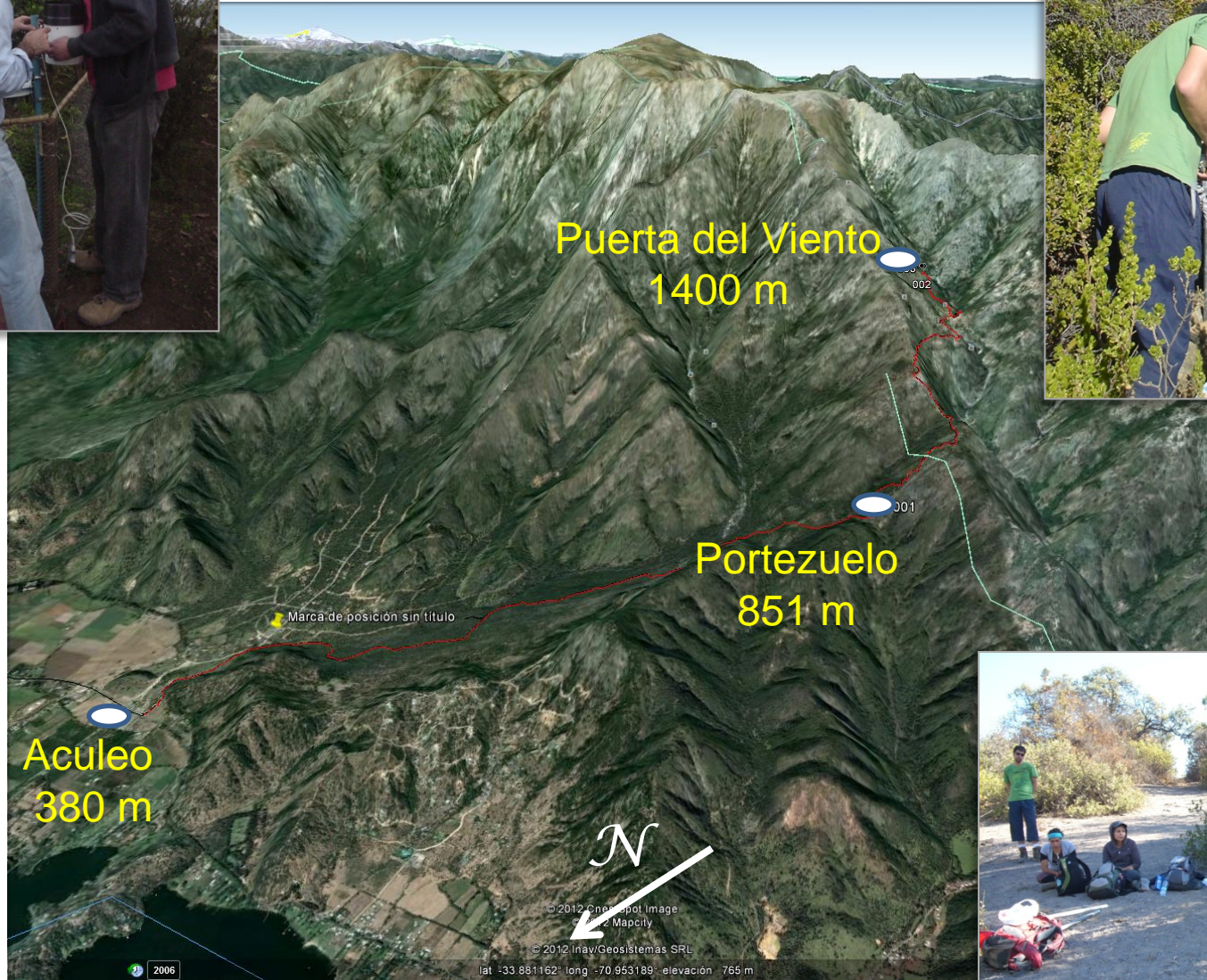
Andrés Arriagada, 2015: Sinoptica de eventos de precipitación en Nahuelbuta(?). Tesis de licenciatura en Geofísica, Universidad de Concepción, Prof. Guía: A. Montecinos

Sergio Gonzalez, 2017: Spatial variability of near-surface temperature over the coastal mountains in southern Chile (38°S). [Magister en Meteorología y Clima](#). Universidad de Chile. Prof. Guía: R. Garreaud

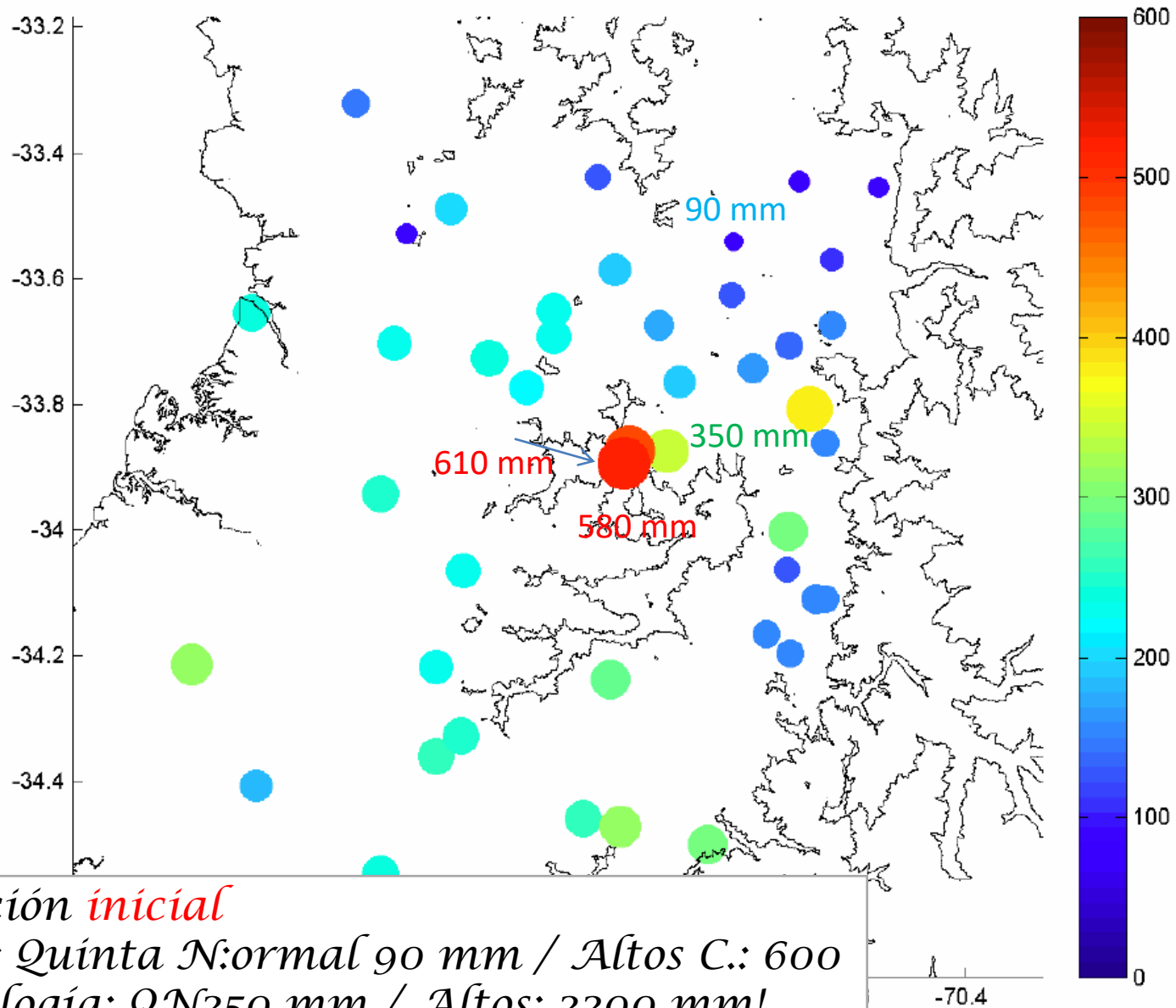
Cintha Bravo, 2018: Microfísica de Nubes sobre la cordillera de Nahuelbuta. [Magister en Meteorología y Clima](#). Universidad de Chile. Prof. Guía: R. Garreaud (en curso)

Adam Massman, 2016: Chilean Coastal Orographic Precipitation Experiment (CCOPE) Pilot Project. Master of Sciences, State University of New York, Albany. Adviser: Justin Minder.

Datos (AFEX + CCOPE)



Precipitación Acumulada Mayo-Junio 2012 [mm]



Estimación inicial

MJ2012: Quinta Normal 90 mm / Altos C.: 600

Climatología: QN 250 mm / Altos: 2200 mm!