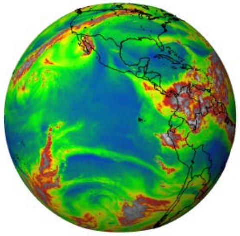
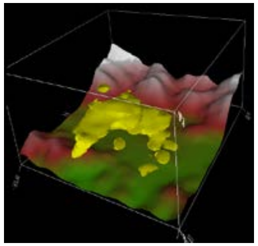
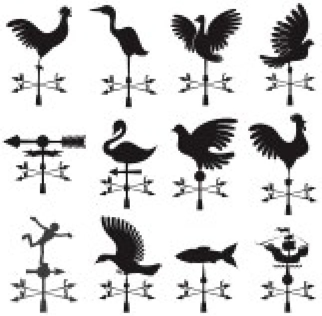


Universidad de Chile
Departamento de Geofísica

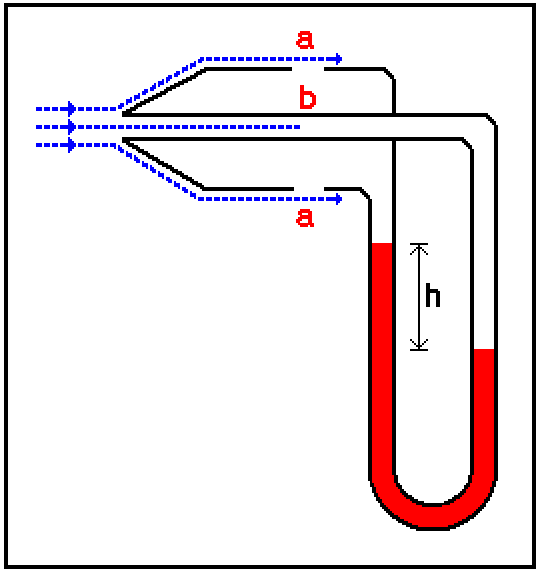
Introducción a la Meteorología

Dinámica Atmosférica



Prof. René Garreaud
www.dgf.uchile.cl/rene

Medición del viento en superficie
Magnitud: anemómetro



Pitot (calibración)

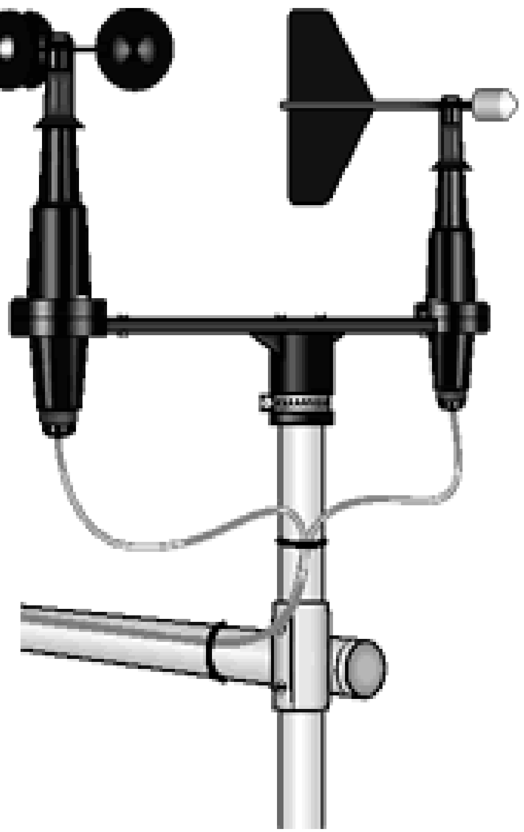
Manga de viento

De Copela o rotación

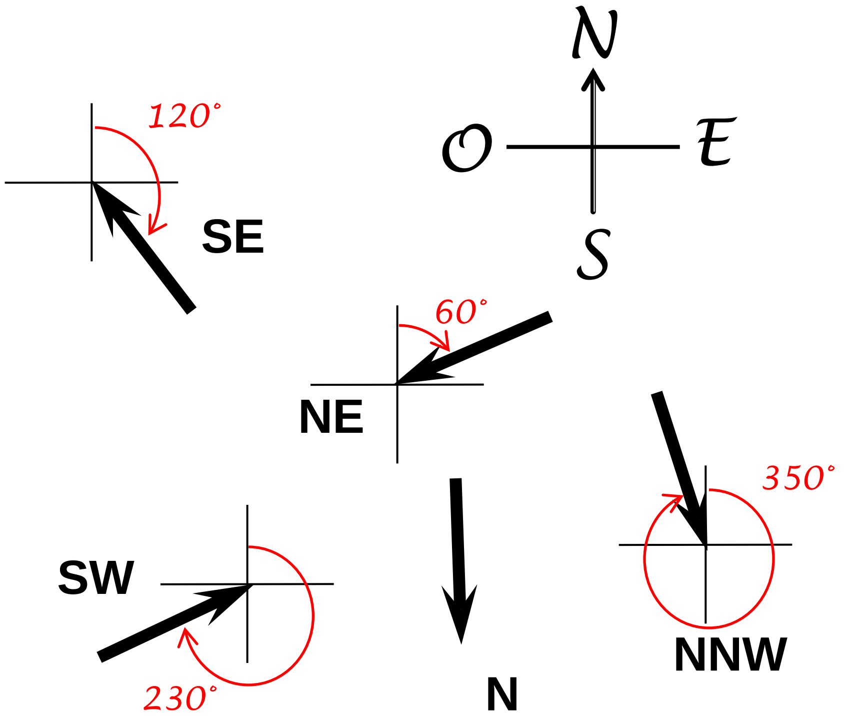
Infrasónico

Dirección del Viento

Anemómetro Veleta



La dirección del viento se designa según la dirección geográfica desde donde el viento esta soplando. (desde donde viene). La dirección (dd) se mide c/r al Norte en forma horaria en grados sexagesimales.



Observations for TEMUCO MAQUEHUE, Chile (SCTC)

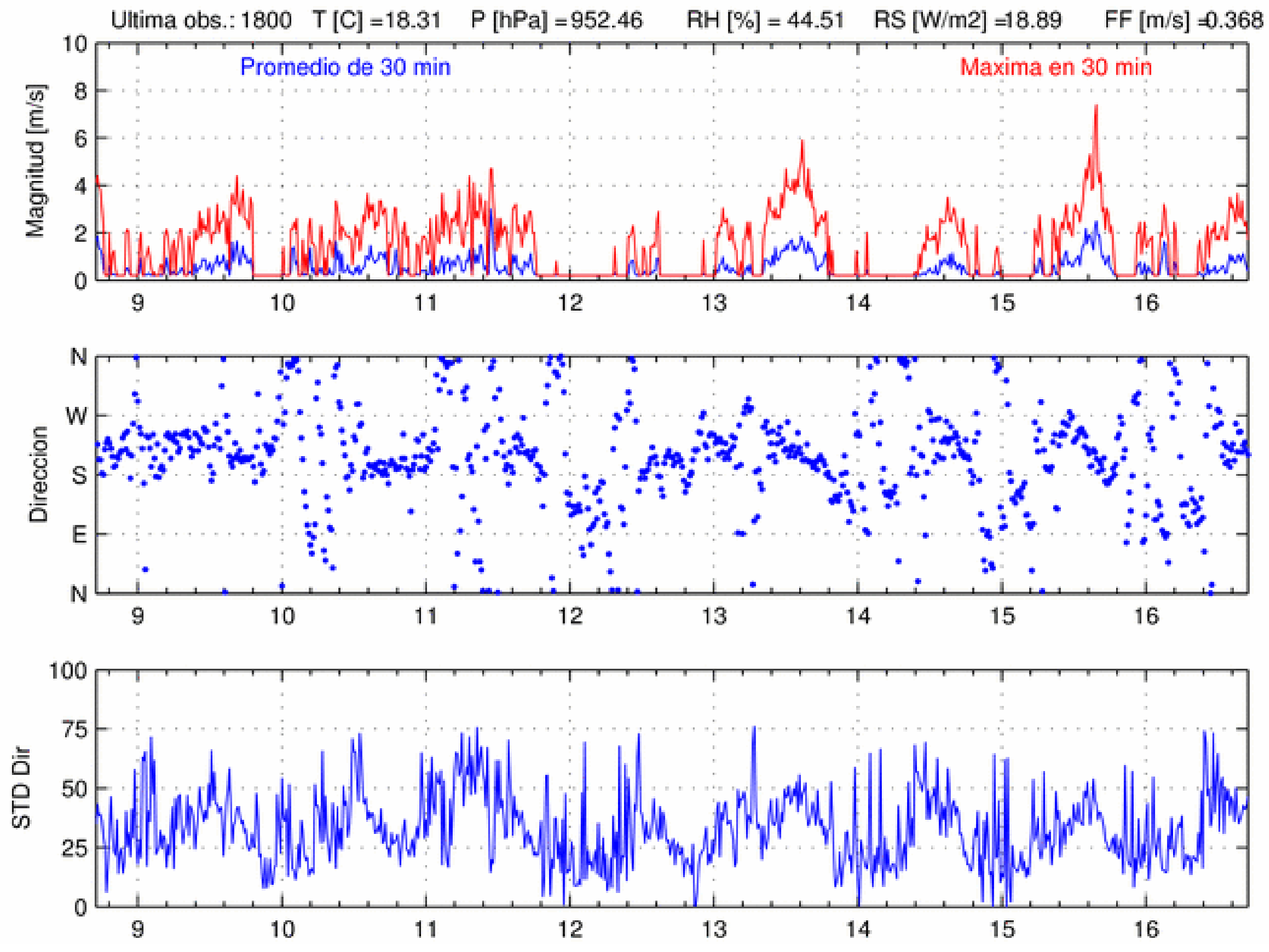
Location: 38.75S 72.63W 120 meters

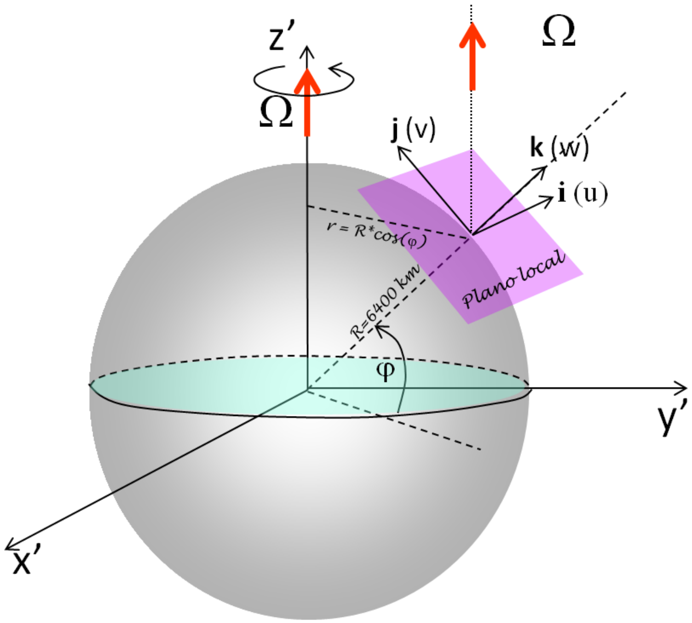
2200Z 15 May 2012 to 2200Z 16 May 2012

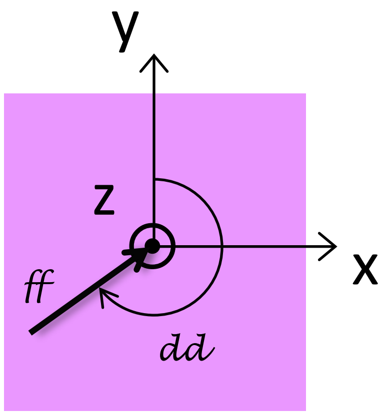
STN	TIME DD/HHMM	ALTM hPa	TMP C	DEW C	RH %	DIR deg	SPD m/s	VIS km	CLOUDS			Weather
SCTC	16/2200	1019.0	11	7	76	20	2	10.0				
SCTC	16/2100	1019.0	12	6	67	10	3	10.0	[illegible]	[illegible]		
SCTC	16/2000	1019.0	14	7	63	350	3	10.0	FEW025	SCT070		
SCTC	16/1900	1019.0	14	6	59	330	3	10.0	SCT025	SCT070		
SCTC	16/1800	1019.0	13	7	67	340	3	10.0	SCT025	BKN070		
SCTC	16/1700	1020.0	12	10	88	80	3	10.0	FEW025	BKN070		
SCTC	16/1600	1020.0	11	9	87	80	3	10.0	FEW025	BKN070		
SCTC	16/1500	1021.0	8	8	100	70	4	7.0	BKN070			H
SCTC	16/1400	1021.0	7	7	100	80	3	2.0	BKN070			F
SCTC	16/1300	1020.0	6	5	93	90	2	0.3	BKN070			F
SCTC	16/1200	1020.0	4	4	100	90	2	0.2	BKN070			F
SCTC	16/1100	1020.0	3	2	93	90	2	0.8	SCT035			F
SCTC	16/1000	1019.0	3	2	93	0	0	0.2	CLR			F
SCTC	16/0900	1019.0	6	5	93	0	0	0.5				
SCTC	16/0800	1019.0	8	7	93	90	2	10.0				
SCTC	16/0700	1019.0	8	7	93	90	2	10.0	[illegible]			
SCTC	16/0600	1019.0	9	8	93	70	3	10.0	BKN020			
SCTC	16/0500	1018.0	9	8	93	70	2	10.0	OVC020			
SCTC	16/0400	1018.0	9	8	93		1	10.0	OVC020			
SCTC	16/0300	1017.0	9	9	100	250	1	8.0	OVC020			RW-
SCTC	16/0200	1017.0	10	9	93		2	10.0	BKN020			
SCTC	16/0100	1015.0	10	10	100	270	3	10.0	FEW006	SCT020		
SCTC	16/0000	1014.0	11	10	94	310	4	7.0	SCT006	BKN020	OVC070	R
SCTC	15/2300	1012.0	12	10	88	360	5	7.0	BKN020	OVC070		R
SCTC	15/2200	1012.0	11	10	94	360	6	7.0	BKN020	OVC070		R

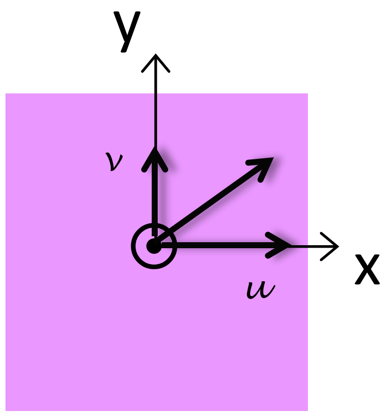
Viento débil del N

Viento débil del E


Ultima obs.: 1800 T [C] =18.31 P [hPa] =952.46 RH [%] = 44.51 RS [W/m2] =18.89 FF [m/s] =0.368
Promedio de 30 min
Maxima en 30 min
Magnitud [m/s]
Direccion
N
W
S
E
N
STD Dir
9
10
11
12
13
14
15
16







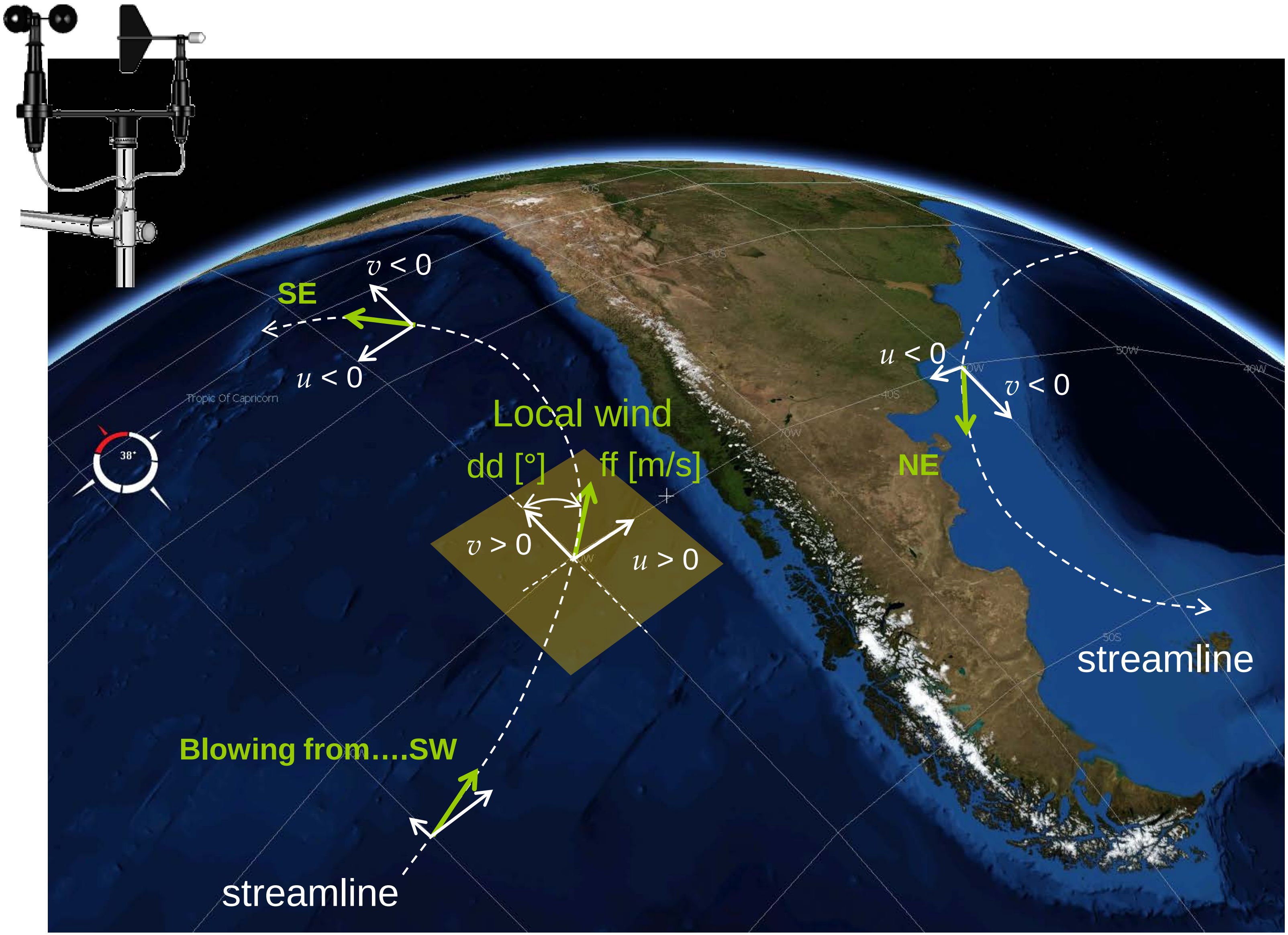
X: Dirección zonal (W-E)…Componente Zonal **u**=dx/dt

Y: Dirección Meridional (S-N) …Componente Meridional **v**=dy/dt

Z: Dirección vertical…Componente vertical **w**=dz/dt

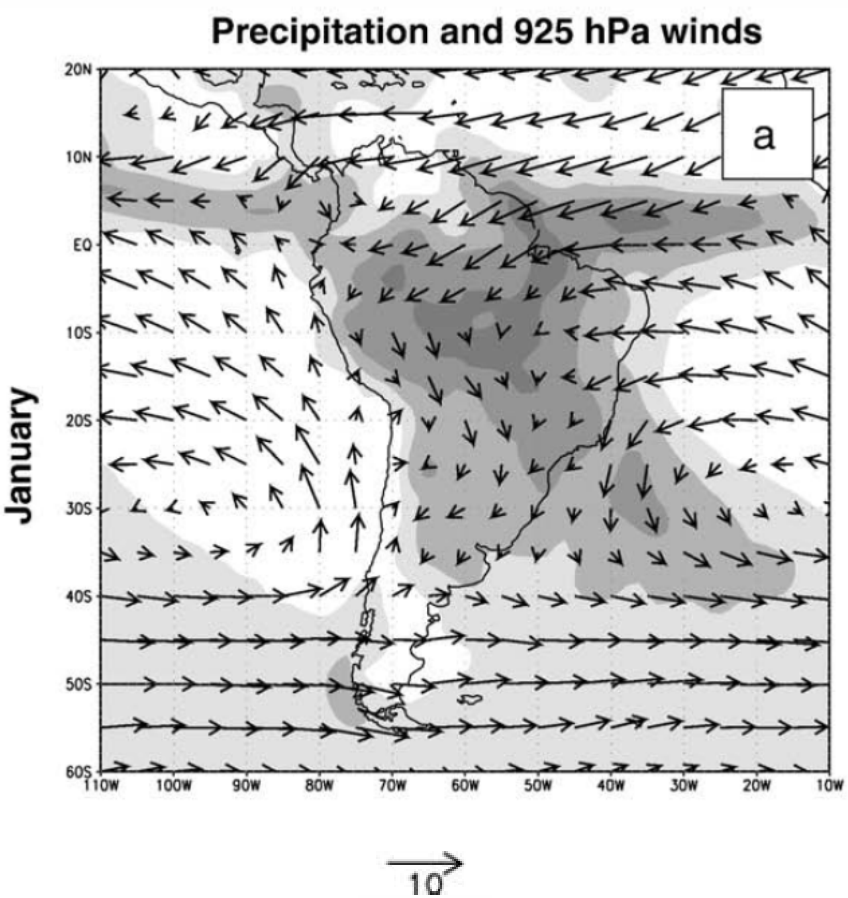
U = -ff*sen(dd) **V=-ff*cos(dd)** **ff=sqrt(U^2+V^2)** **dd=atan(ff/dd)**

Wind is a vector: magnitude (speed) and blowing direction (° wrt north)
Alternatively, zonal (u, west-east) and meridional (v, south-north) components

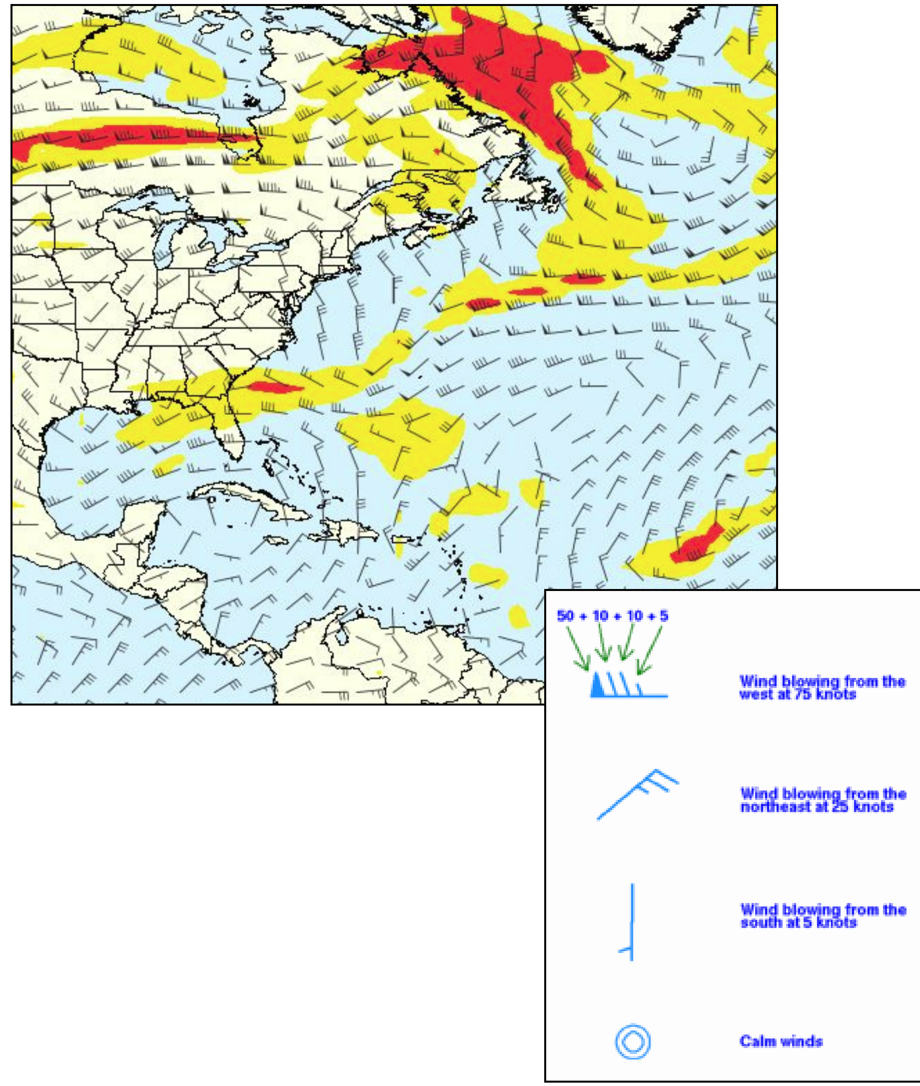


Representación de viento en Mapas

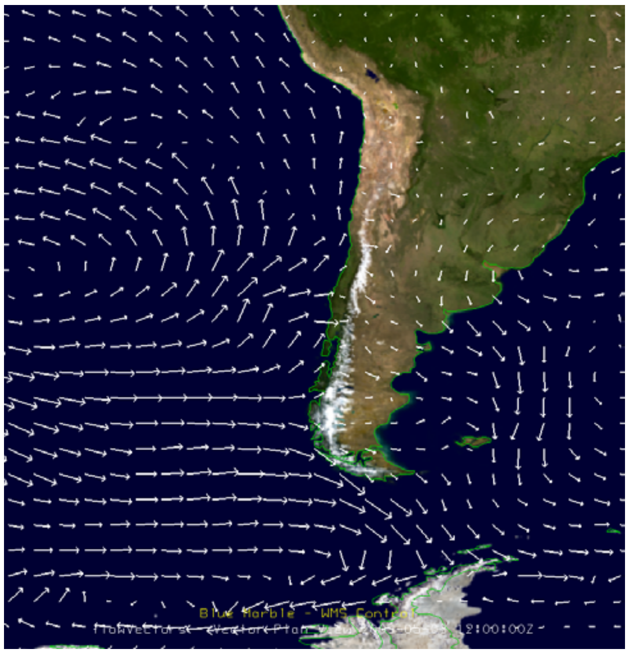
Vectores



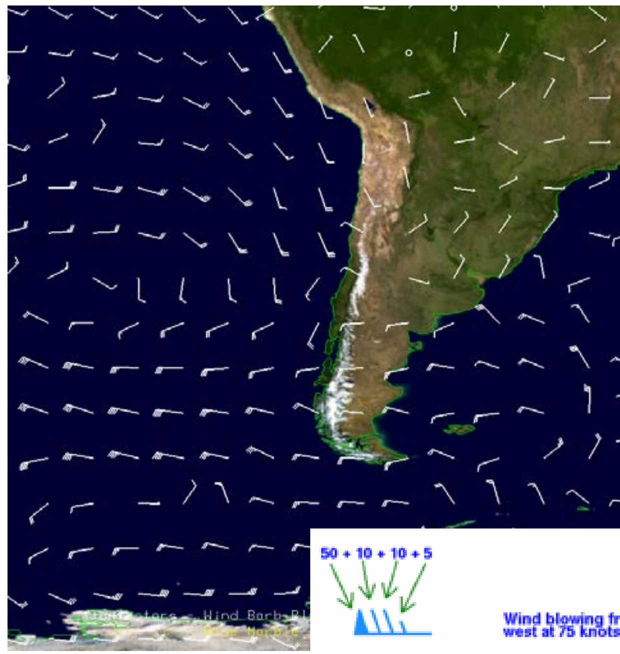
Barbas



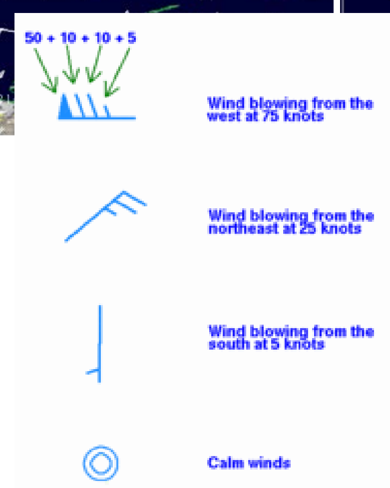
Representación de viento en Mapas

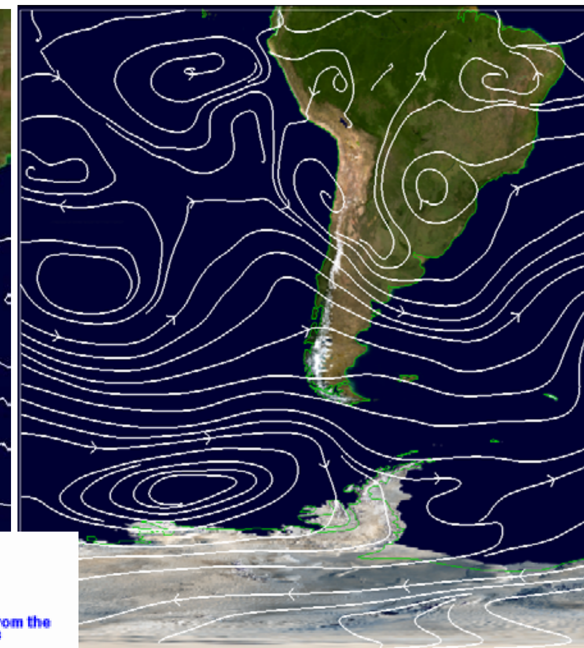


Vectores



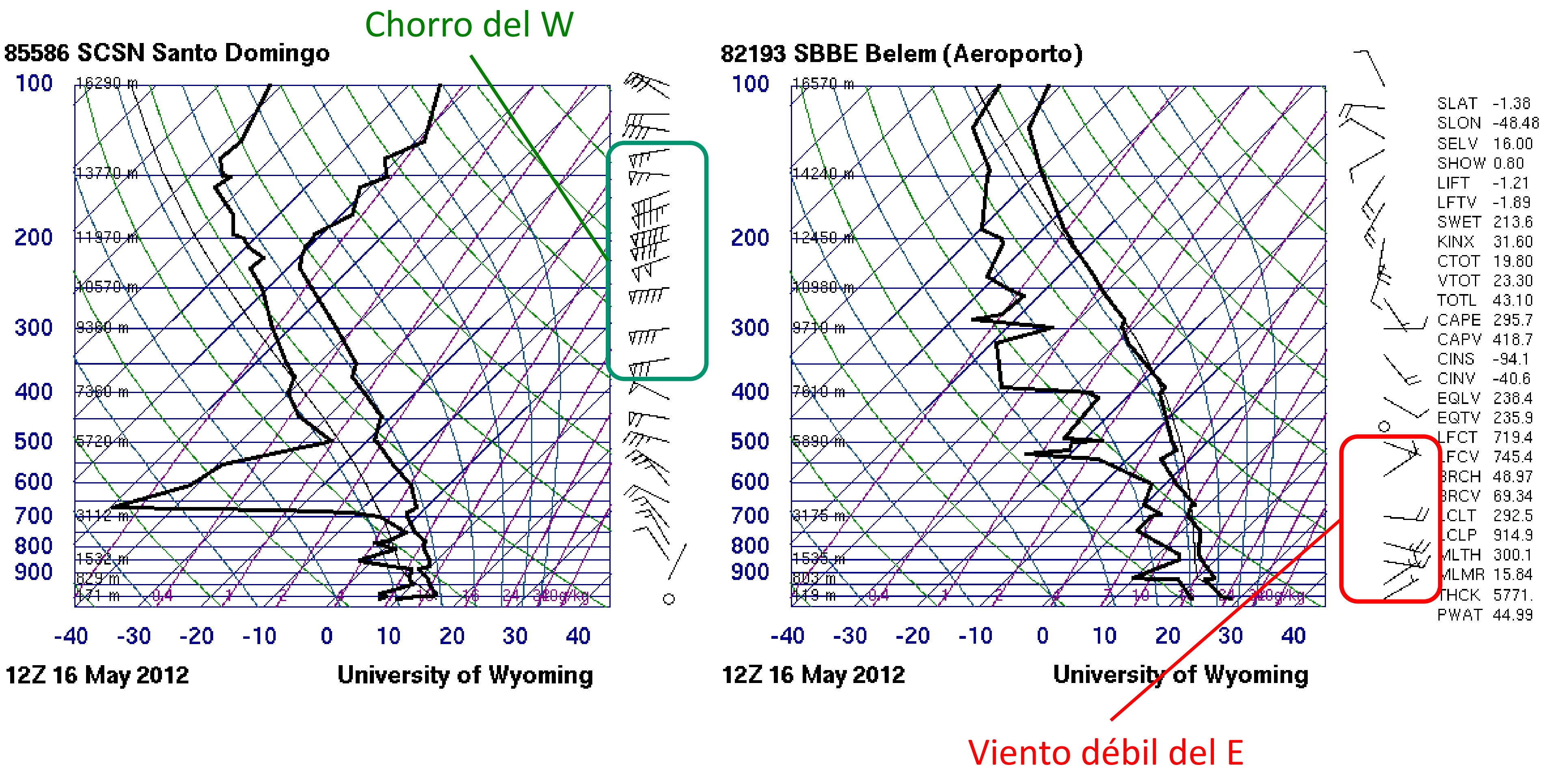
Barbas





Líneas de corriente

Radiosondas miden viento en altura



Dinámica

Apuntes de H. E. de Swart

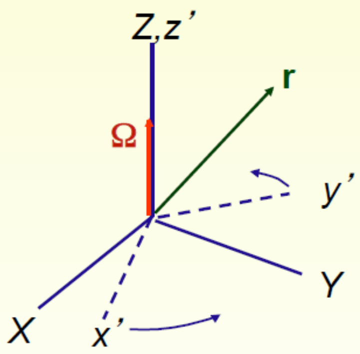
Momentum balance; absolute frame

Newton's second law in an absolute frame

$$\boxed{\frac{D_a \mathbf{u}_a}{Dt} = \sum_i \mathbf{F}_i}$$

$\mathbf{F}_i$: forces (per mass unit)

Operator D_a/Dt is total time derivative in absolute frame; $\mathbf{u}_a$ is velocity in absolute frame



Ω: rotation vector
X,Y,Z: axes in absolute frame
x',y',z': axes in rotating frame
r : position vector

By definition: $\boxed{\mathbf{u}_a = \frac{D_a \mathbf{r}}{Dt}}$ $\boxed{\mathbf{u} = \frac{D\mathbf{r}}{Dt}}$

$\boxed{\mathbf{u}_a = \mathbf{u} + \boldsymbol{\Omega} \times \mathbf{r}}$ => $\boxed{\frac{D_a \mathbf{r}}{Dt} = \frac{D\mathbf{r}}{Dt} + \boldsymbol{\Omega} \times \mathbf{r}}$

Note: in the boxed relation **r** can be replaced by any vector, in particular by $\mathbf{u}_a$ =>

$$\begin{aligned}
\frac{D_a \mathbf{u}_a}{Dt} &= \frac{D\mathbf{u}_a}{Dt} + \boldsymbol{\Omega} \times \mathbf{u}_a \\
&= \frac{D}{Dt}\left(\mathbf{u} + \boldsymbol{\Omega} \times \mathbf{r}\right) + \boldsymbol{\Omega} \times \left(\mathbf{u} + \boldsymbol{\Omega} \times \mathbf{r}\right) \\
&= \frac{D\mathbf{u}}{Dt} + \boldsymbol{\Omega} \times \mathbf{u} + \boldsymbol{\Omega} \times \left(\mathbf{u} + \boldsymbol{\Omega} \times \mathbf{r}\right)
\end{aligned}$$

Dinámica

Apuntes de H. E. de Swart

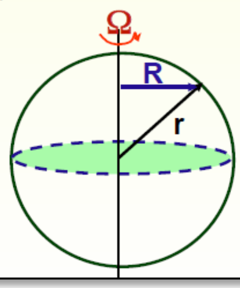
The momentum balance in a rotating frame

$$\frac{D\mathbf{u}}{Dt} + 2\boldsymbol{\Omega}\times\mathbf{u} + \boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{r}) = \sum_i \mathbf{F}_i$$

Here, two apparent forces emerge:

$-2\boldsymbol{\Omega}\times\mathbf{u}$ **Coriolis force**/mass

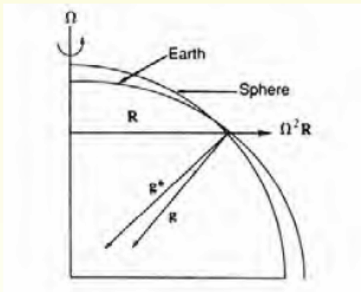
$-\boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{r}) = \Omega^2\mathbf{R}$ **centrifugal force**/mass



|**R**| : distance to rotation axis

Manifestation of centrifugal force F_{ce}

If earth would be a sphere, then $\mathbf{F}_{ce}$ would have a component along the earth's surface



However, $\mathbf{F}_{ce}$ causes shape of the earth to adjust from sphere → spheroid, such that **gravity**

$$\mathbf{g} = \mathbf{g}_* + \Omega^2\mathbf{R}$$

is perpendicular to the surface of the earth.

Thus, momentum equations on a rotating earth becom

$$\frac{D\mathbf{u}}{Dt} + 2\boldsymbol{\Omega}\times\mathbf{u} = \mathbf{g} + \mathbf{F}_p + \mathbf{F}_{\text{tide}} + \mathbf{F}_{\text{fric}}$$

with

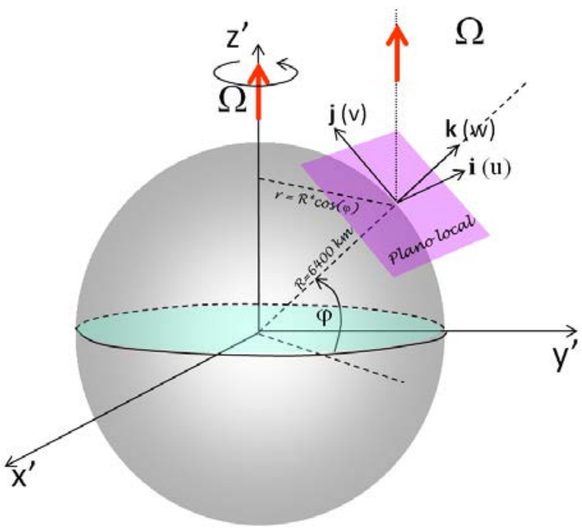
$\mathbf{F}_p$: pressure force/mass

$\mathbf{F}_{\text{tide}}$: tidal force/mass

$\mathbf{F}_{\text{fric}}$: frictional force/mass

Dinámica

Apuntes de H. E. de Swart



Thus, in this coordinate system, the Coriolis force

$$-2\,\boldsymbol{\Omega}\times\mathbf{u} = \begin{vmatrix} \mathbf{e}_x & \mathbf{e}_y & \mathbf{e}_z \\ 0 & -2\Omega\cos\phi & -2\Omega\sin\phi \\ u & v & w \end{vmatrix}$$

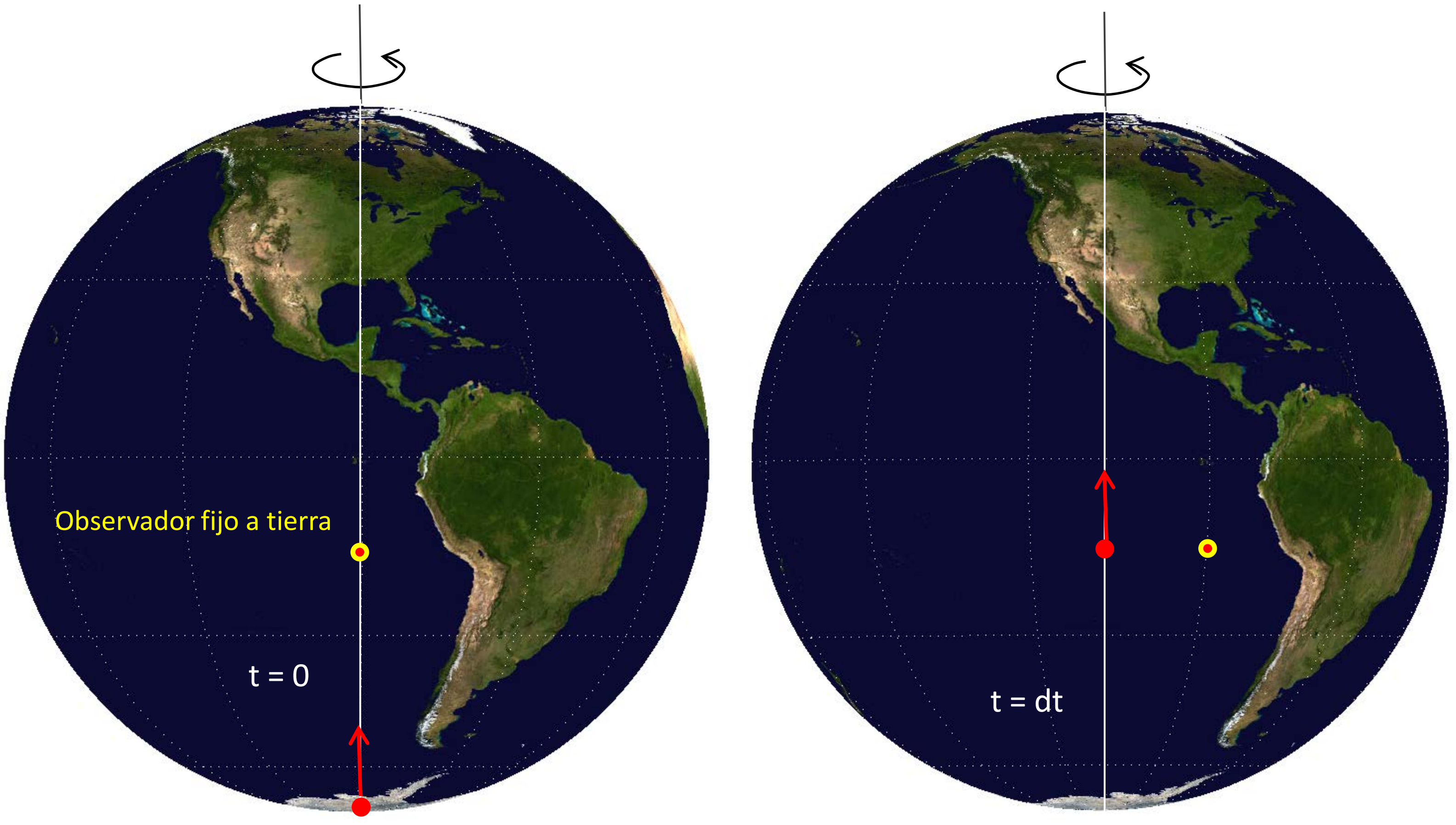
Coriolis parameter *f*
(2x vertical component of Ω)

$$= \mathbf{e}_x(-2\Omega\cos\phi\, w + 2\Omega\sin\phi\, v) - \mathbf{e}_y\, 2\Omega\sin\phi\, u + \mathbf{e}_z\, 2\Omega\cos\phi\, u$$

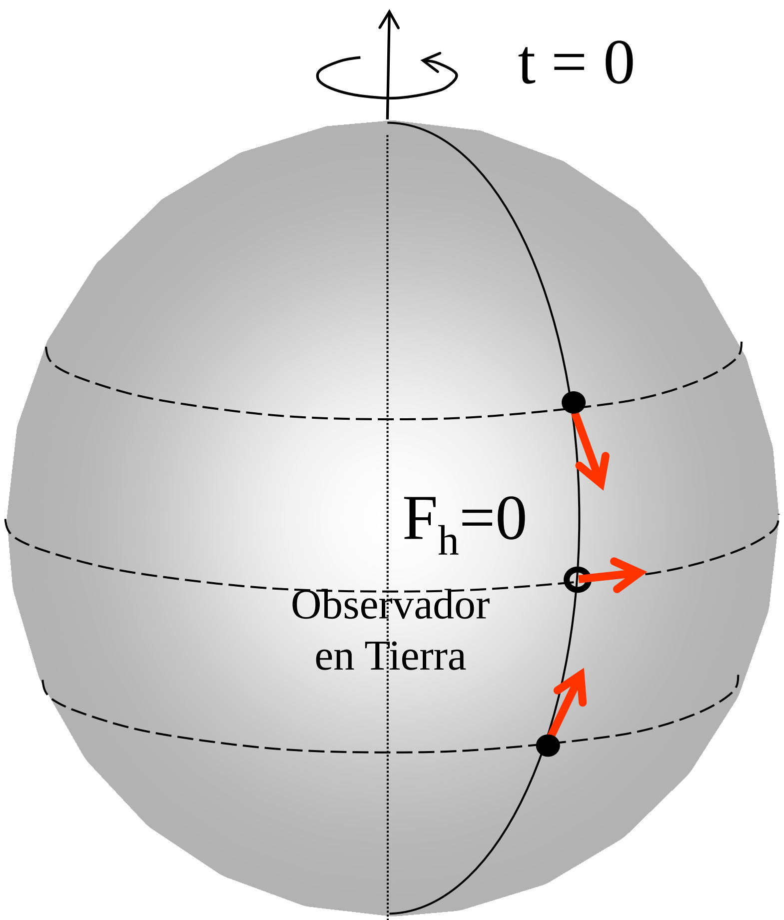
$$\mathbf{F}_{co} = \mathbf{e}_x(-2\Omega\,\underline{\cos\phi\, w} + 2\Omega\,\underline{\sin\phi\, v}) - \mathbf{e}_y\, 2\Omega\,\underline{\sin\phi\, u} + \mathbf{e}_z\, 2\Omega\,\underline{\cos\phi\, u}$$

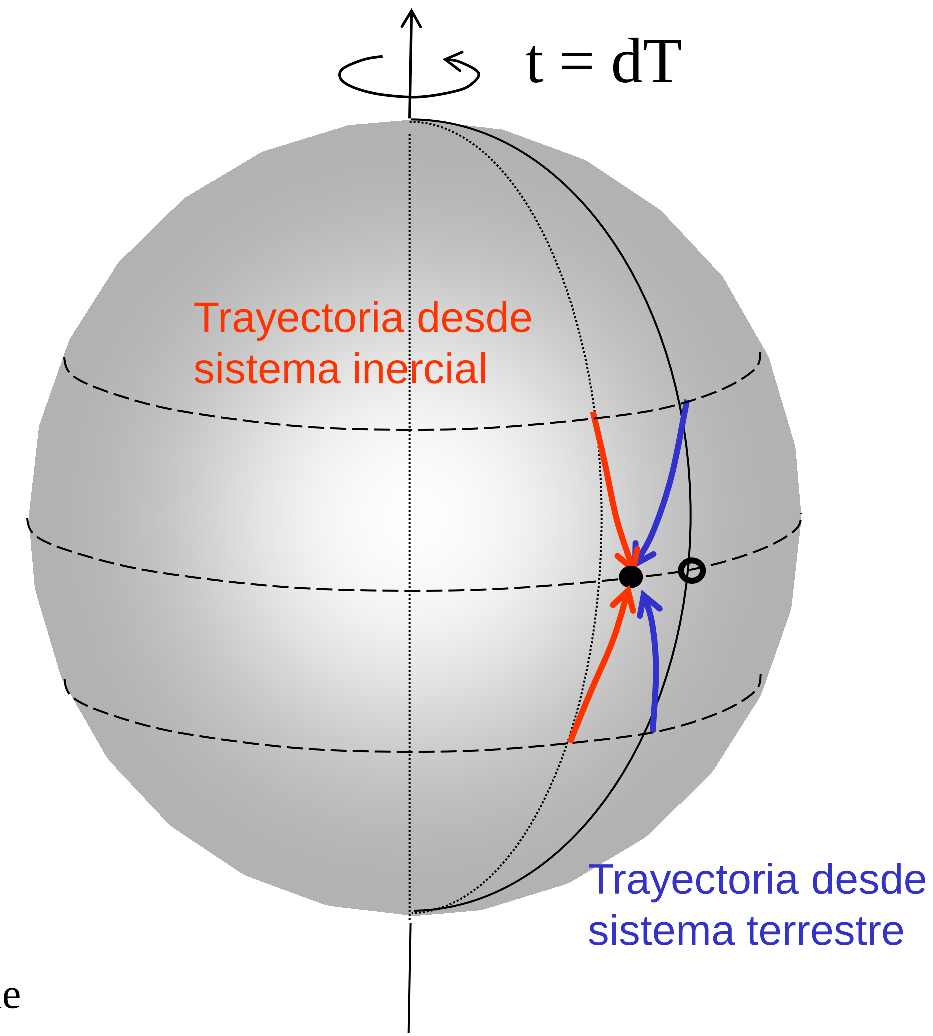
Parametro de Coriolis: f = 2Ωsen(ϕ)

Efecto de Coriolis



* Partícula es lanzada directamente desde el PS al ecuador.
* Despreciando la fuerza de roce, partícula mantiene un MRU.
* Observador fijo a tierra describe una “misteriosa” desviación hacia la izquierda





● Partículas flotando sobre superficie parten impulsivamente al ecuador….

Cuando observamos un movimiento desde un sistema de referencia que acelera (por ejemplo en rotación), se deja de cumplir la segunda ley de Newton (F=ma). Podemos "bajarnos" del sistema movil, o introducir fuerzas aparentes, de manera de seguir cumpliendo F=ma

En meteorología, decidimos mantener nuestra descripción del viento desde el planeta (sistema movil), por lo cual debemos agregar la Fuerza de Coriolis a nuestro análisis de movimiento.

Propiedade de la Fuerza de Coriolis

- Actua sobre cuerpos no fijos a la tierra

- Siempre deflecta el movimiento hacia la izquierda (derecha) en el hemisferio sur (norte)

- Su magnitud es zero en el ecuador y máxima en los polos

- Su magnitud es dependiente de la velocidad de rotación de la tierra (o el planeta en cuestión). FC=0 para rotación nula.

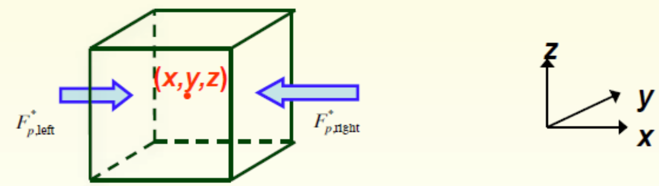
Dinámica

Apuntes de H. E. de Swart

Pressure gradient force

Note: pressure itself is a force per surface area. It are the <u>spatial variations in pressure</u> that result in a force/mass.

Derivation (fixed control volume):



Pressure force 'right':

$$F^*_{p,\mathrm{right}} = -\,p\big|_{(x+\frac{1}{2}\Delta x,y,z)}\Delta y\Delta z \approx -\left(p\big|_{(x,y,z)} + \frac{\partial p}{\partial x}\bigg|_{(x,y,z)}\frac{1}{2}\Delta x\right)\Delta y\Delta z$$

Pressure force 'left':

$$F^*_{p,\mathrm{left}} = p\big|_{(x-\frac{1}{2}\Delta x,y,z)}\Delta y\Delta z \approx \left(p\big|_{(x,y,z)} - \frac{\partial p}{\partial x}\bigg|_{(x,y,z)}\frac{1}{2}\Delta x\right)\Delta y\Delta z$$

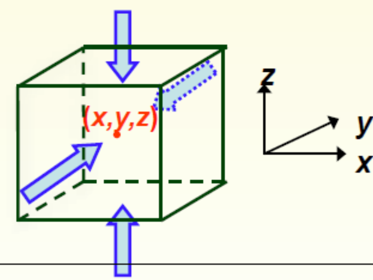
Total force/mass in x-direction:

$$F_{p,x} = \frac{F^*_{p,\mathrm{left}} + F^*_{p,\mathrm{right}}}{\rho\Delta x\Delta y\Delta z} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

Likewise, total force/mass in y- and z-direction:

$$F_{p,y} = \frac{F^*_{p,\mathrm{front}} + F^*_{p,\mathrm{back}}}{\rho\Delta x\Delta y\Delta z} = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$F_{p,z} = \frac{F^*_{p,\mathrm{down}} + F^*_{p,\mathrm{up}}}{\rho\Delta x\Delta y\Delta z} = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$



Final result in vector notation:

$$\boxed{\mathbf{F}_p = -\frac{1}{\rho}\nabla p}$$

directed from high→low pressure

Thus, momentum equations on a rotating earth become

$$\frac{D\mathbf{u}}{Dt} + 2\mathbf{\Omega} \times \mathbf{u} = \mathbf{g} + \mathbf{F}_p + \mathbf{F}_{\text{tide}} + \mathbf{F}_{\text{fric}}$$

with

- $\mathbf{F}_p$: pressure force/mass
- $\mathbf{F}_{\text{tide}}$: tidal force/mass
- $\mathbf{F}_{\text{fric}}$: frictional force/mass

momentum equations in components:

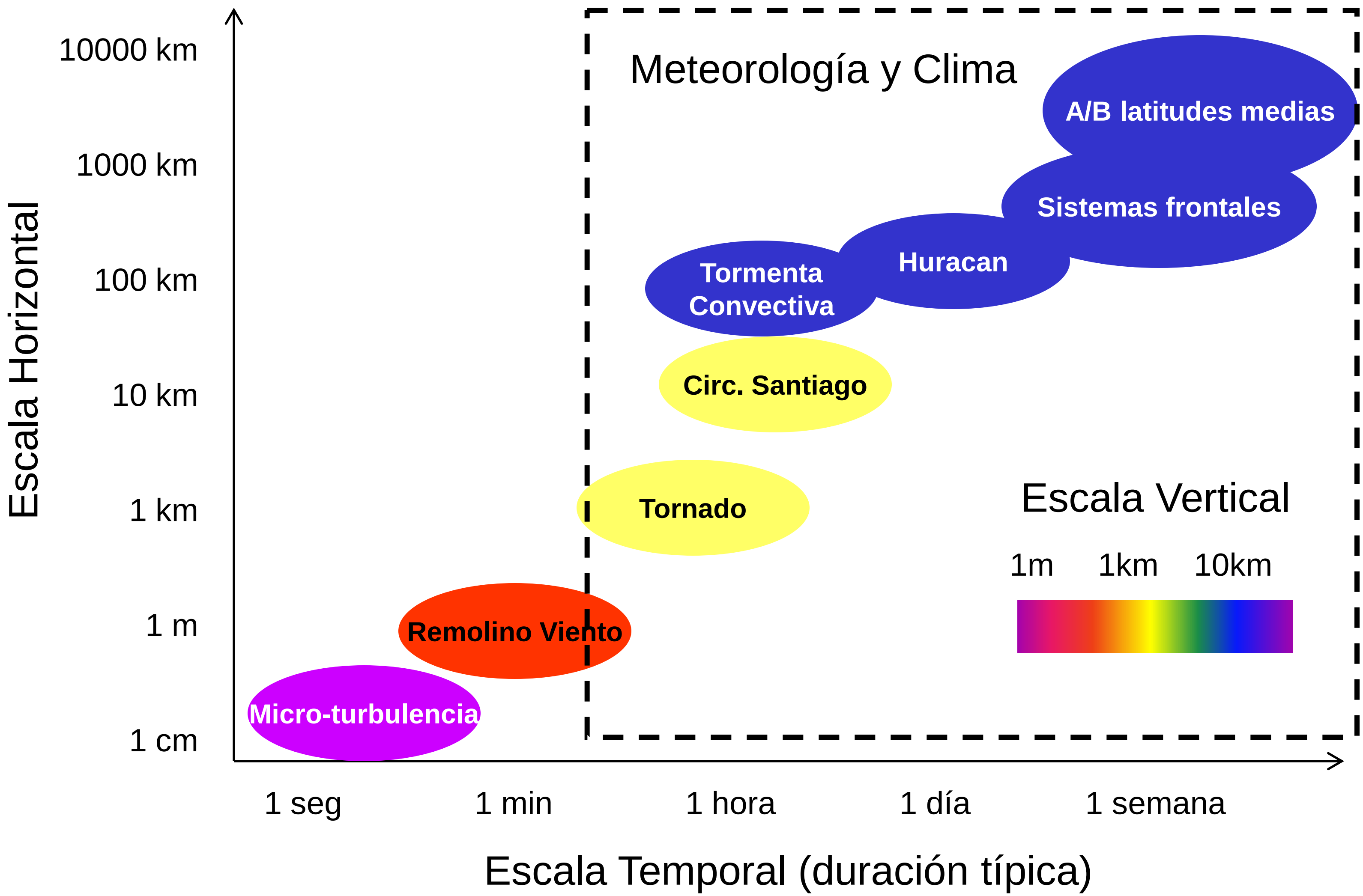
$$\frac{Du}{Dt} - \frac{uv\tan\phi}{r} + \frac{uw}{r} - 2\Omega\sin\phi\, v + 2\Omega\cos\phi\, w = -\frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{\partial \Phi_t}{\partial x} + F_x$$

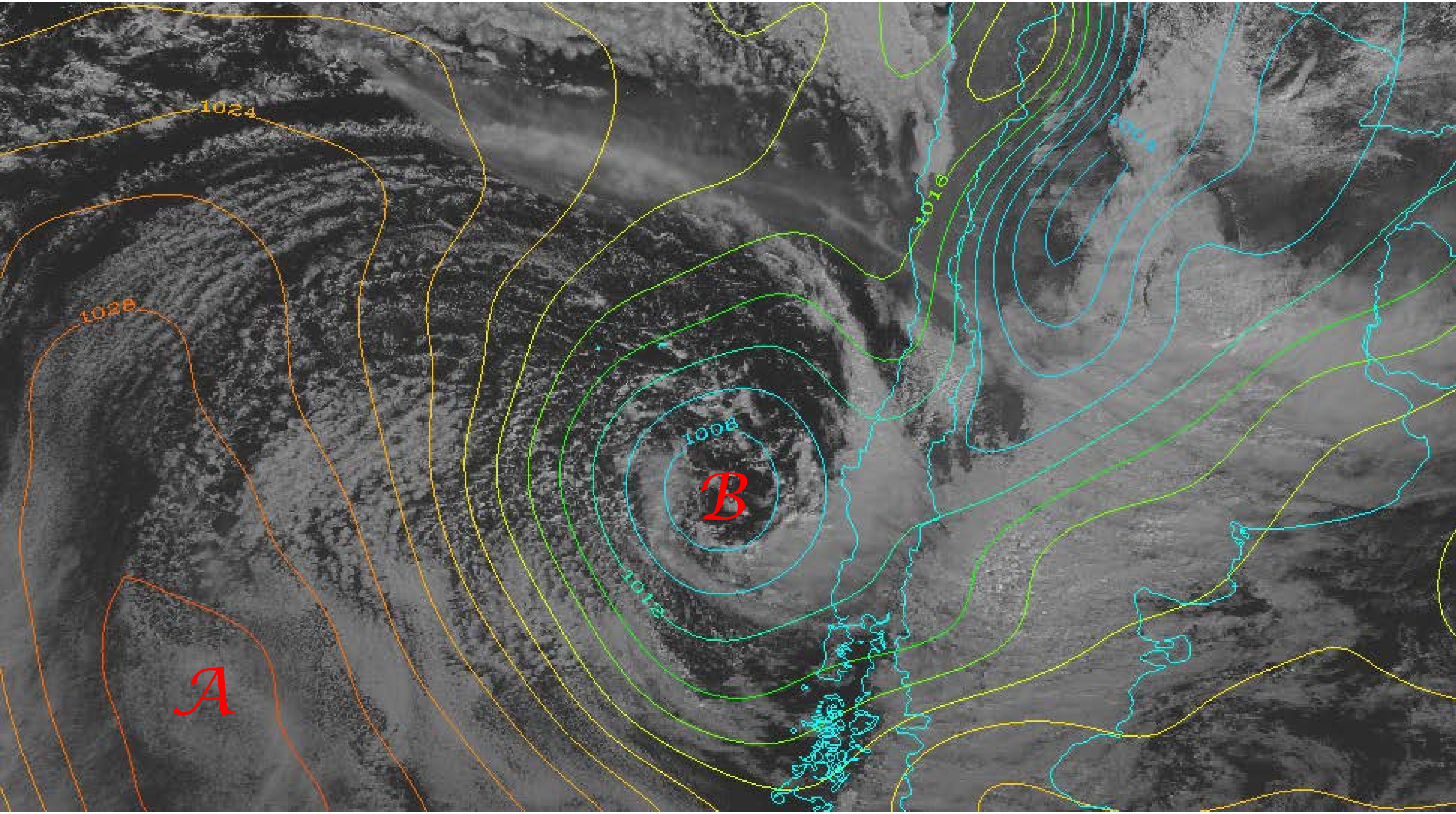
$$\frac{Dv}{Dt} + \frac{u^2\tan\phi}{r} + \frac{vw}{r} + 2\Omega\sin\phi\, u = -\frac{1}{\rho}\frac{\partial p}{\partial y} - \frac{\partial \Phi_t}{\partial y} + F_y$$

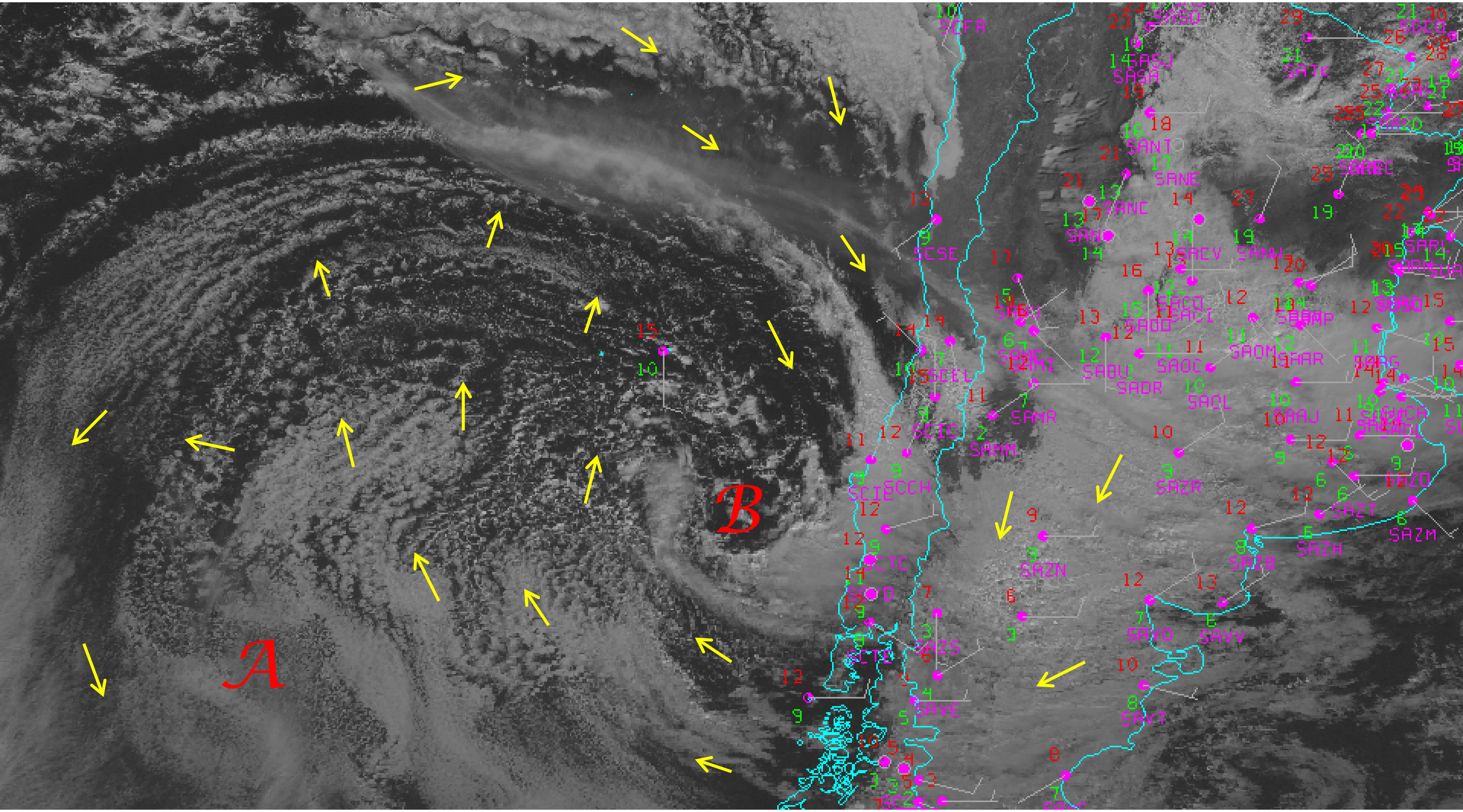
$$\frac{Dw}{Dt} - \frac{u^2 + v^2}{r} - 2\Omega\cos\phi\, u = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g - \frac{\partial \Phi_t}{\partial z} + F_z$$

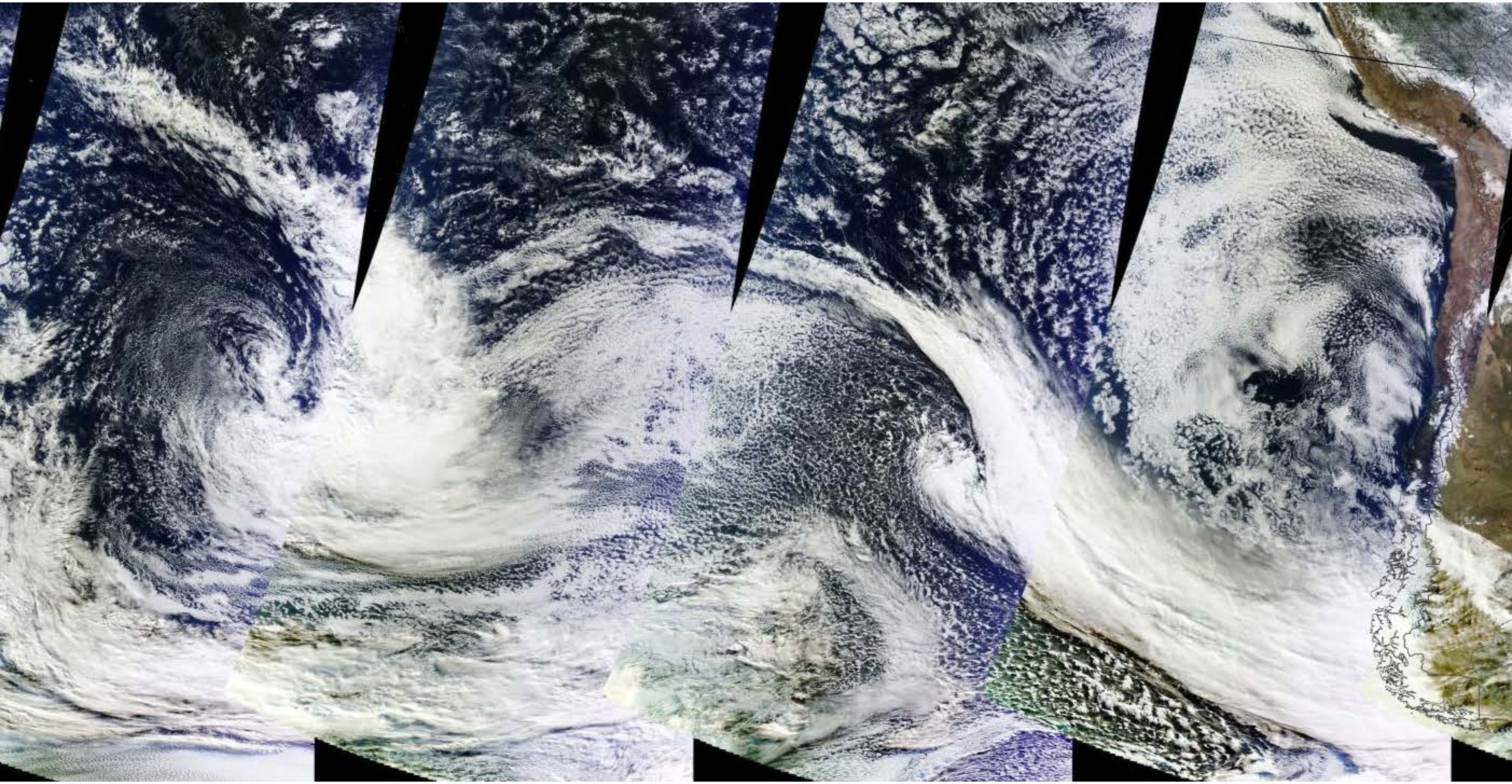
metric | Coriolis | pressure gradient | gravity | tide | friction

Escala temporal-espacial de fenómenos atmosféricos



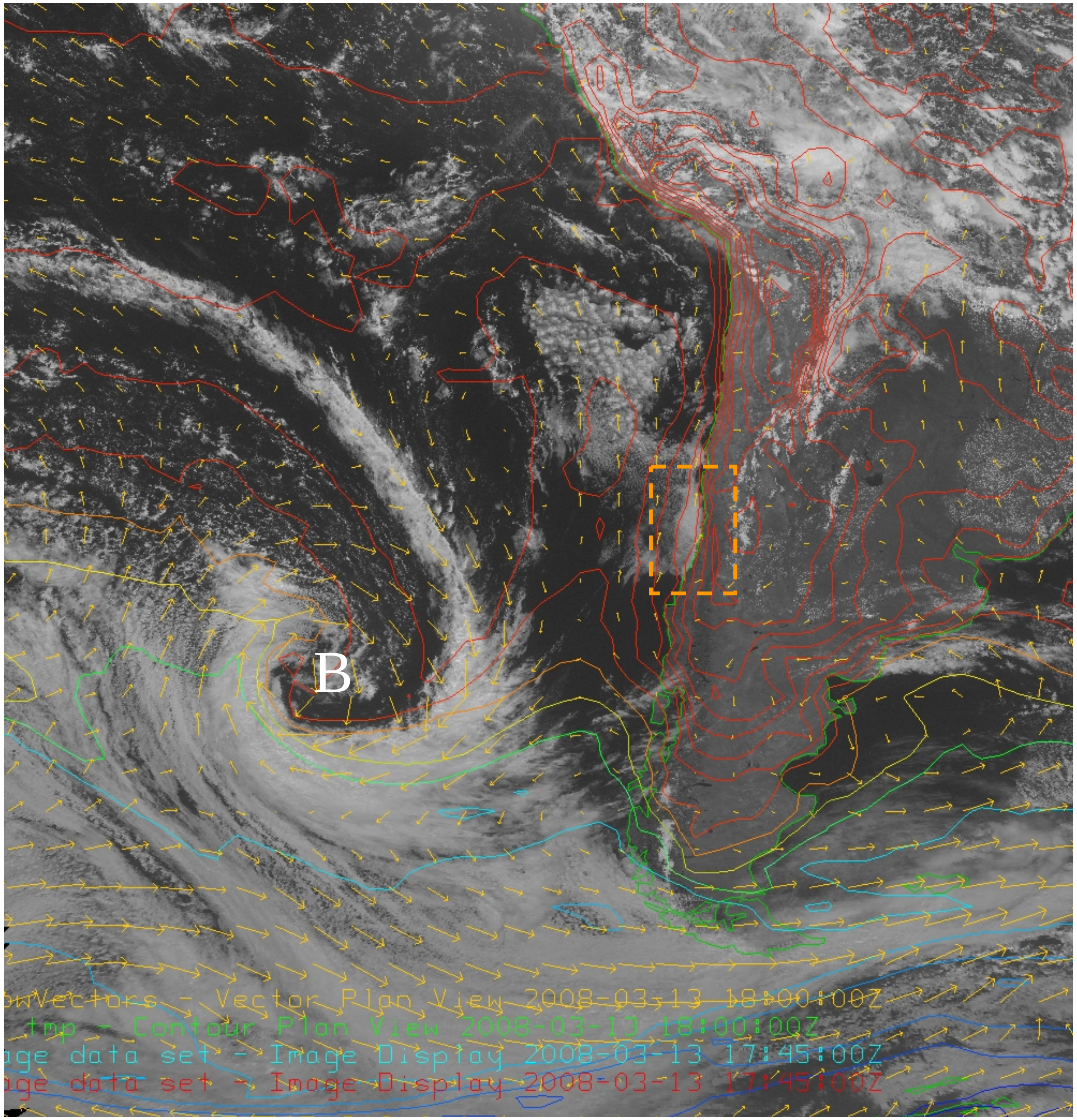

1024
1028
1008
1012
1016
1004
B
A


B
A



Depresión extratropical / Frente frío

Imagen visible (GOES) + viento 850 hPa



Análisis de Escala de Sistemas de Latitudes Medias

$$\begin{aligned} U = 10\ \mathrm{m\,s^{-1}};\ W &= 10^{-2}\ \mathrm{m\,s^{-1}}; \\ L = 10^6\ \mathrm{m}\ (10^3\ \mathrm{km});\ H &= 10^4\ \mathrm{m}\ (10\ \mathrm{km}); \\ T = L/U\ \sim\ 10^5\ (\ 1\ \mathrm{day});\ \delta P &= 10^3\ Pa\ (10\ \mathrm{mb}) \\ \text{and}\qquad \rho^* &= 1\ \mathrm{kg\ m^{-3}}. \end{aligned}$$

(a) horizontal momentum equations

$$\begin{aligned} \frac{Du}{Dt} - 2\Omega v \sin\phi + 2\Omega w \cos\phi &= -\frac{1}{\rho}\frac{\partial p}{\partial x} \\ \frac{Dv}{Dt} + 2\Omega u \sin\phi \qquad\qquad\quad &= -\frac{1}{\rho}\frac{\partial p}{\partial y} \end{aligned}$$

scales	U^2/T	$2\Omega U \sin\phi$	$2\Omega W \cos\phi$	$\delta P/(\rho L)$
orders	10^{-4}	10^{-3}	10^{-6}	10^{-3}

(b) vertical momentum equation (total pressure form)

$$\frac{Dw}{Dt} - 2\Omega u \cos\phi = -\frac{1}{\rho}\frac{\partial p_T}{\partial z} - g$$

scales	UW/L	$2\Omega u \cos\phi$	$\delta P_0/(\rho H)$	g
orders	10^{-7}	10^{-3}	10	10

$$\boxed{\frac{D\mathbf{u}_h}{Dt} + f\mathbf{k}\wedge\mathbf{u}_h = -\frac{1}{\rho}\nabla_h p}$$

$$\boxed{0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \sigma,}$$

THE ROSSBY NUMBER

- Dividing the horizontal momentum equation, (6), through by fV we get

$$\frac{1}{fV}\frac{D\vec{V}}{Dt} = -\frac{1}{\rho f V}\nabla p - \hat{k}\times\frac{f\vec{V}}{fV}.$$

- Using the representative scales the order of magnitude of these terms are

$$\frac{U}{fL} \quad = \quad \frac{\delta P}{\rho f U} \quad + \quad 1$$

- The dimensionless combination U/fL is defined as the *Rossby number* (named for Gustav Rossby),

$$Ro \equiv U/fL \qquad \textbf{(7)}$$

GEOSTROPHIC BALANCE (VERY SMALL ROSSBY NUMBER)

- When the Rossby number is much less than unity ($Ro \ll 1$), then the acceleration (inertial) term can be ignored and the only two terms left are the pressure gradient term and the Coriolis term, which must be nearly in balance.
  - This is known as *geostrophic balance*, and the velocity in this case is known as the *geostrophic wind*.
  - The momentum equation in this case reduces to

$$\hat{k}\times f\vec{V}_g = -\frac{1}{\rho}\nabla p$$

which is solved for the geostrophic wind to yield

$$\vec{V}_g = \frac{1}{f\rho}\hat{k}\times\nabla p\,,$$

CYCLOSTROPHIC BALANCE (VERY LARGE ROSSBY NUMBER)

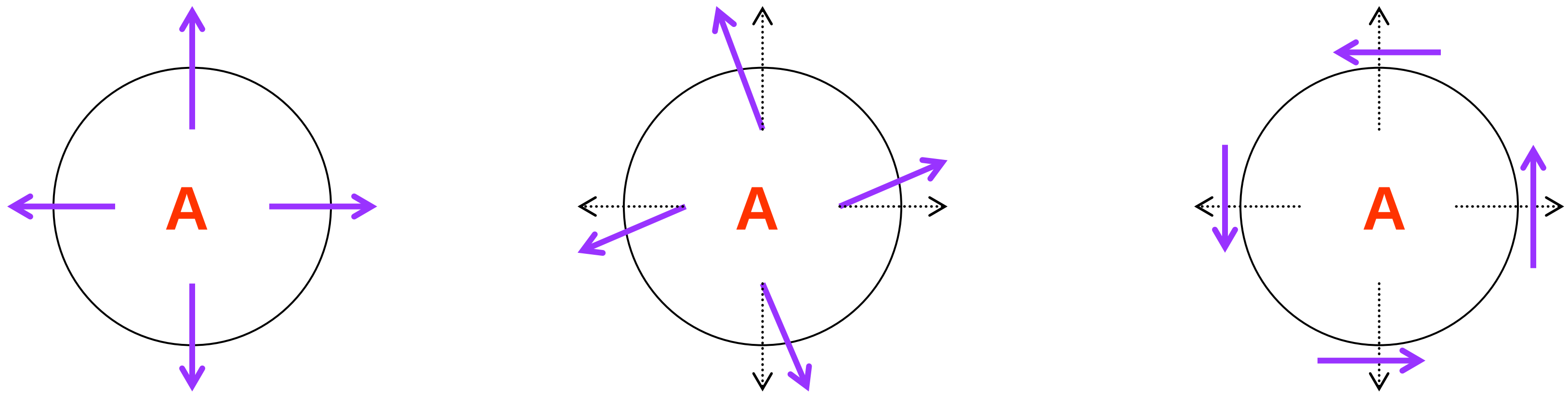
- When the Rossby number is much greater than unity ($Ro \gg 1$) then the Coriolis term can be ignored. In this instance the only terms that are left are the acceleration and the pressure gradient terms, and so the acceleration is a direct result of the pressure gradient force

$$\frac{D\vec{V}}{Dt} = -\frac{1}{\rho}\nabla p. \qquad \textbf{(10)}$$

  - This type of balance is called *cyclostrophic*.
  - In cyclostrophic balance the pressure gradient acceleration is exactly that required for the centripetal acceleration, and so we have

$$\frac{V_c^2}{r} = \frac{|\nabla p|}{\rho}$$

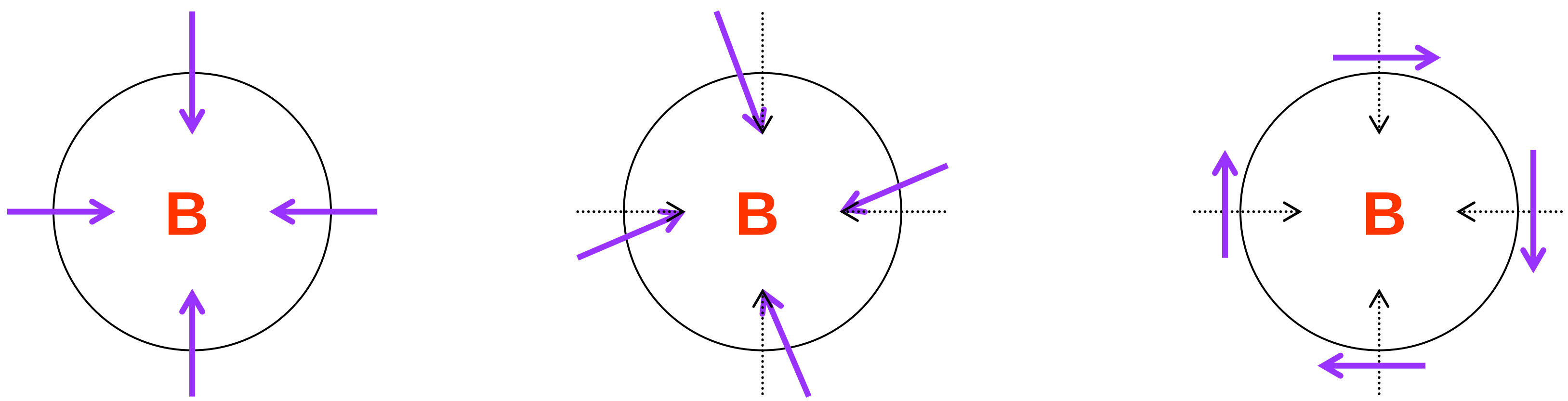
¿Como circula el aire en torno a los centros de alta y baja presión (HS)?



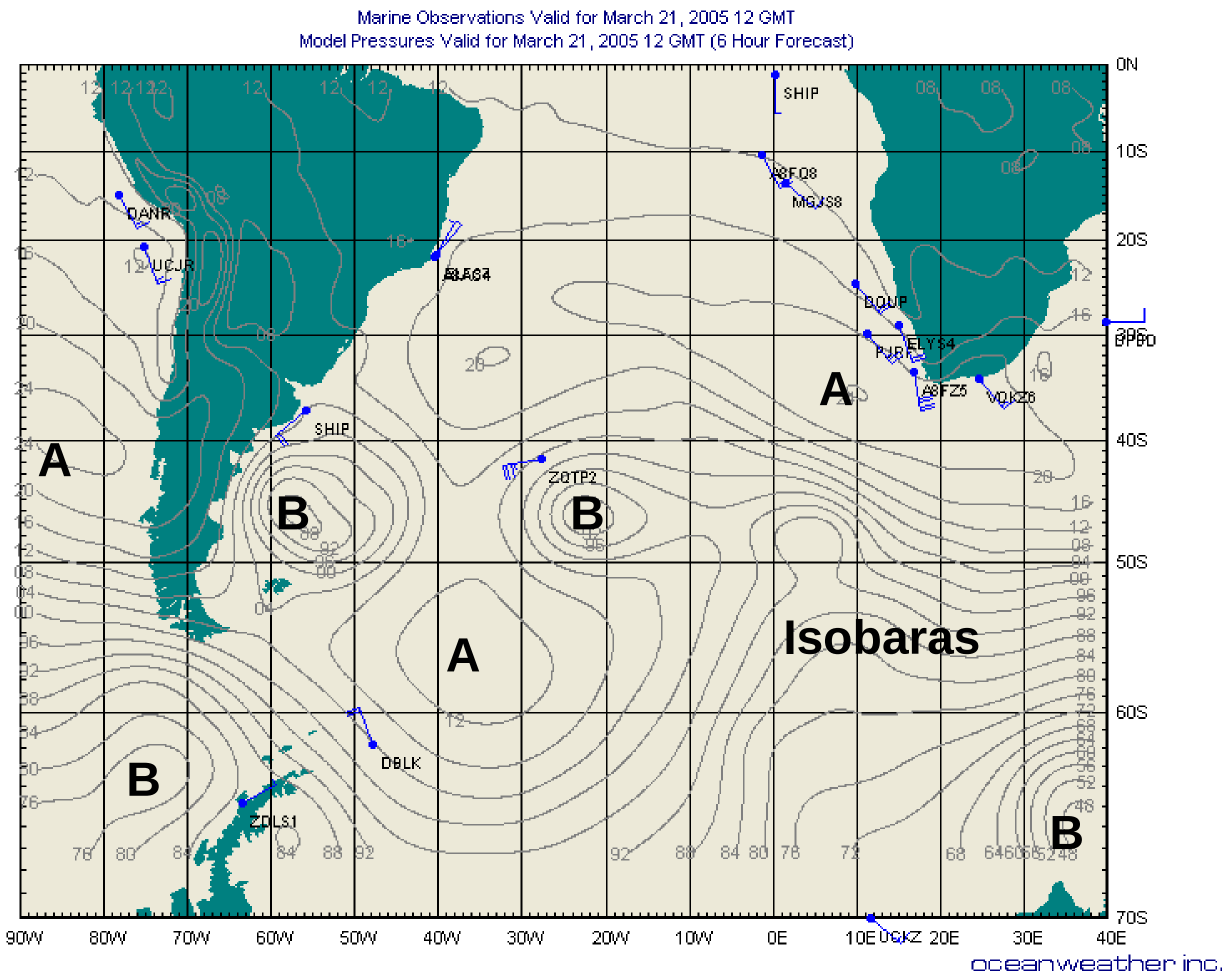
En el ecuador o en planeta sin rotación

Muy cerca del ecuador o rotación planetaria muy lenta

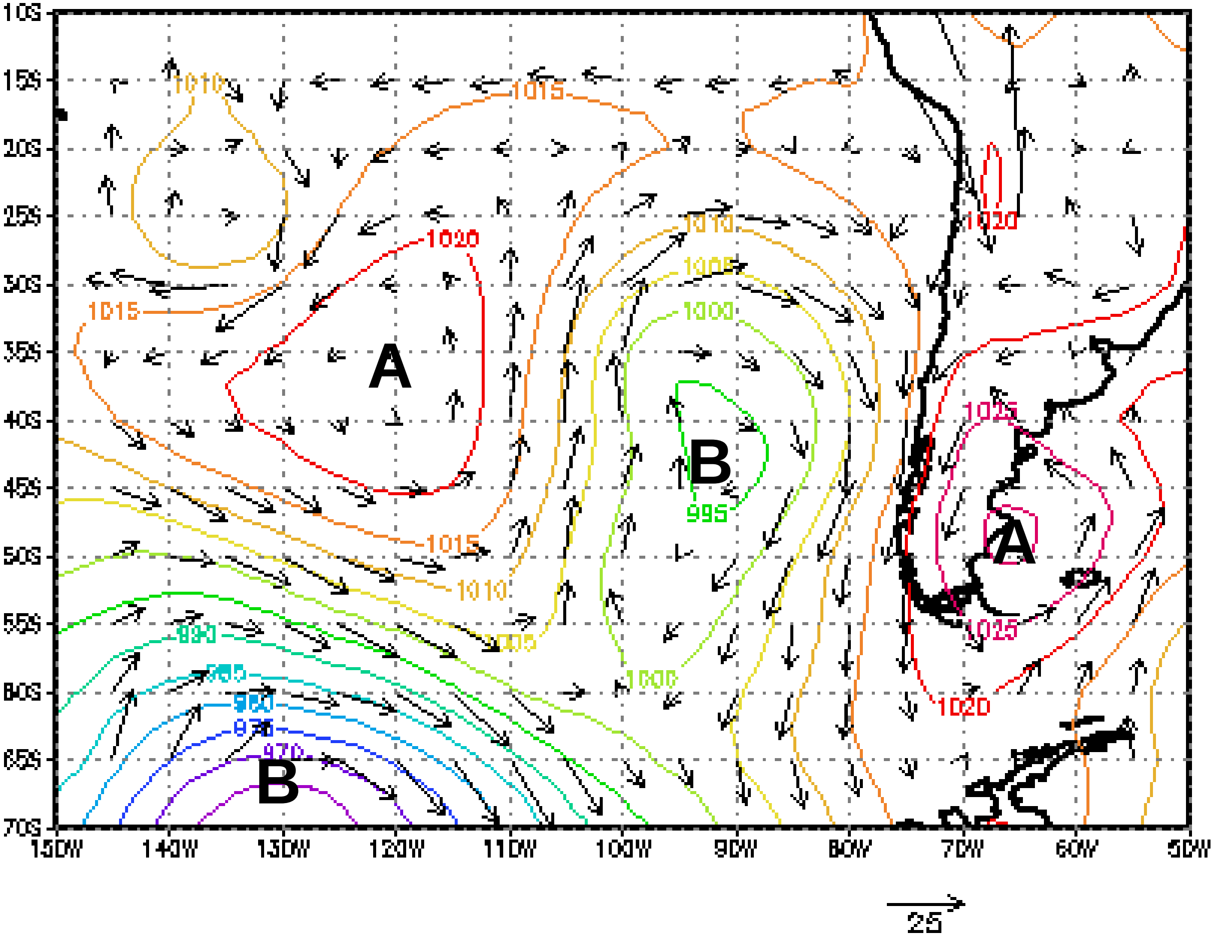
Lejos del ecuador (>20°) para movimientos lentos



¿Porque nos gustan tanto los mapas del tiempo?

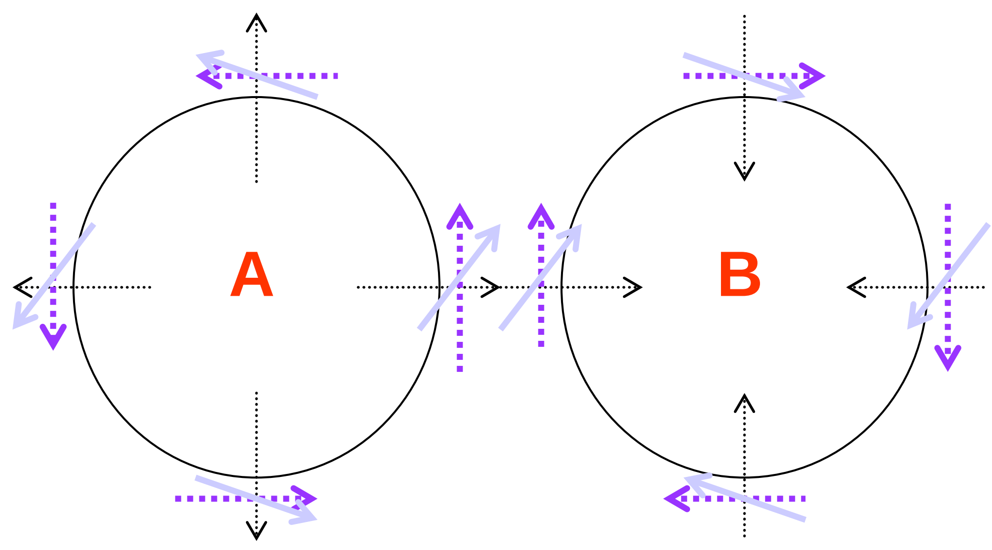


Contornos: líneas de igual presión
Flechas: vector viento



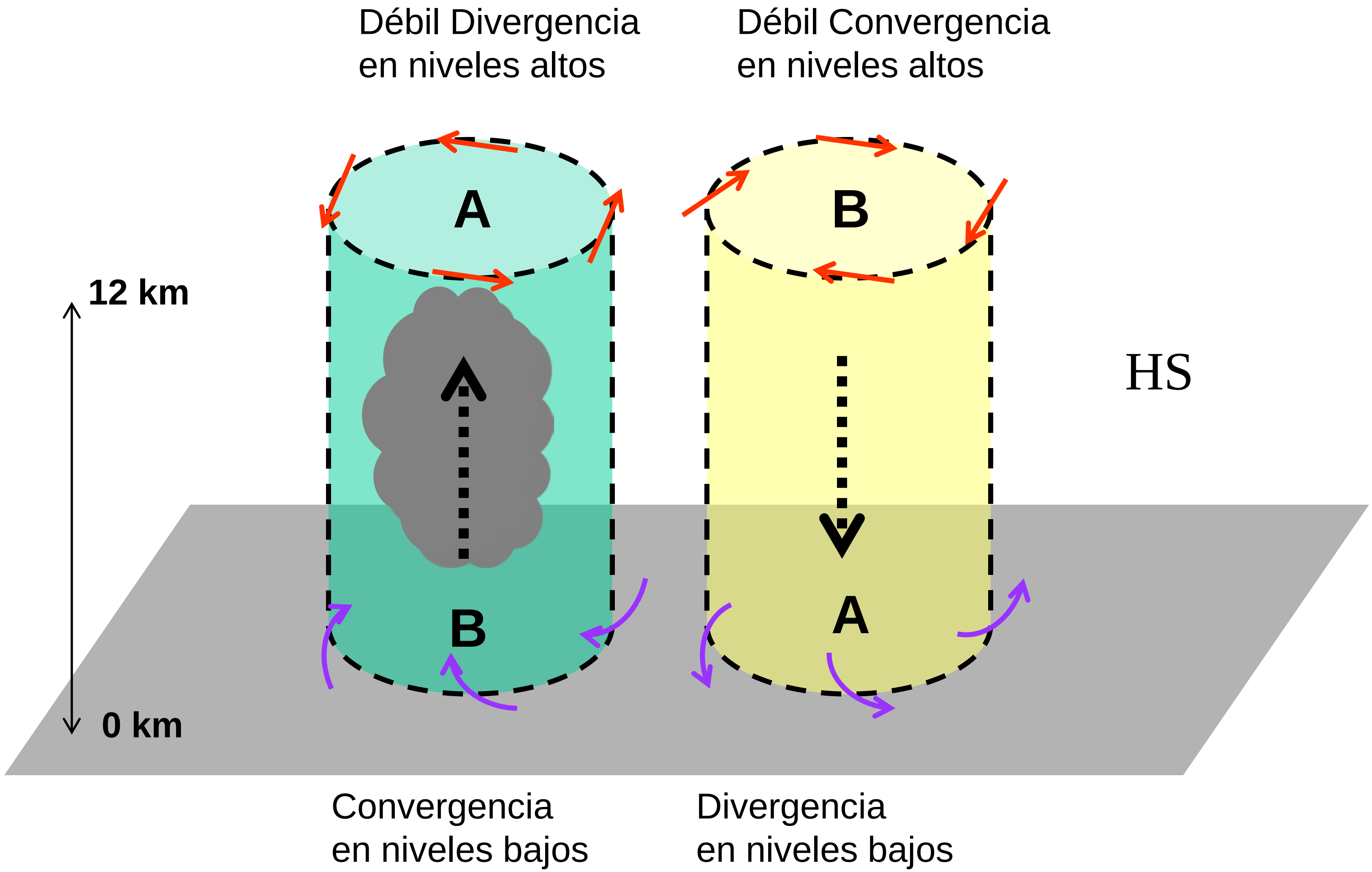
Efecto de la Fricción

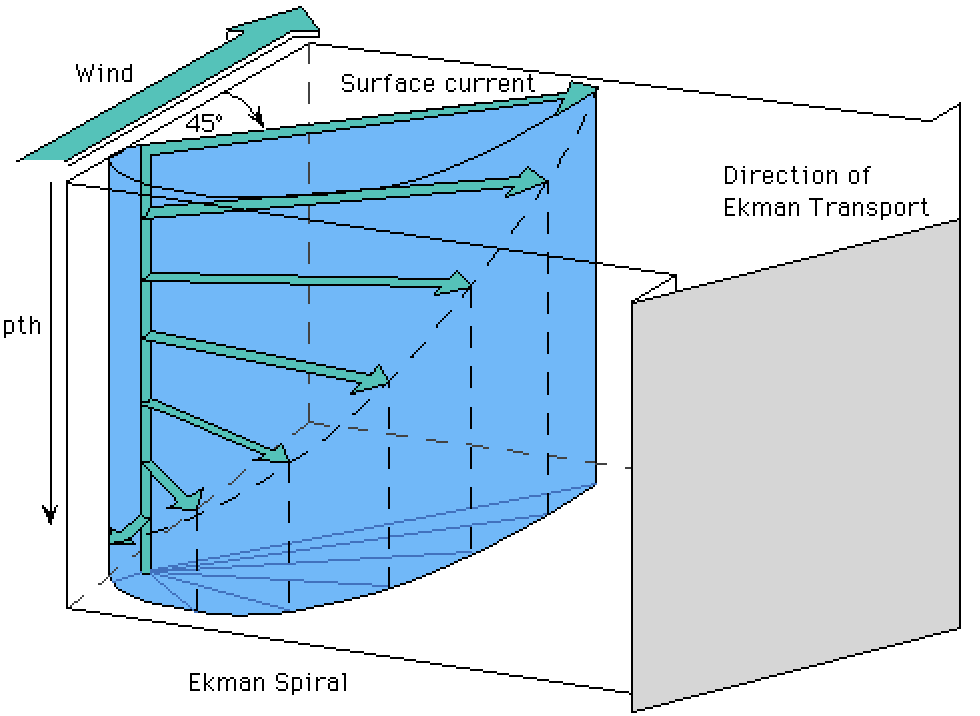
Si queremos agregar mas realismo a nuestro balance de fuerzas que determinan el viento real, debemos considerar el efecto de la fricción que sufre el aire en contacto con el suelo (o cercano a el).



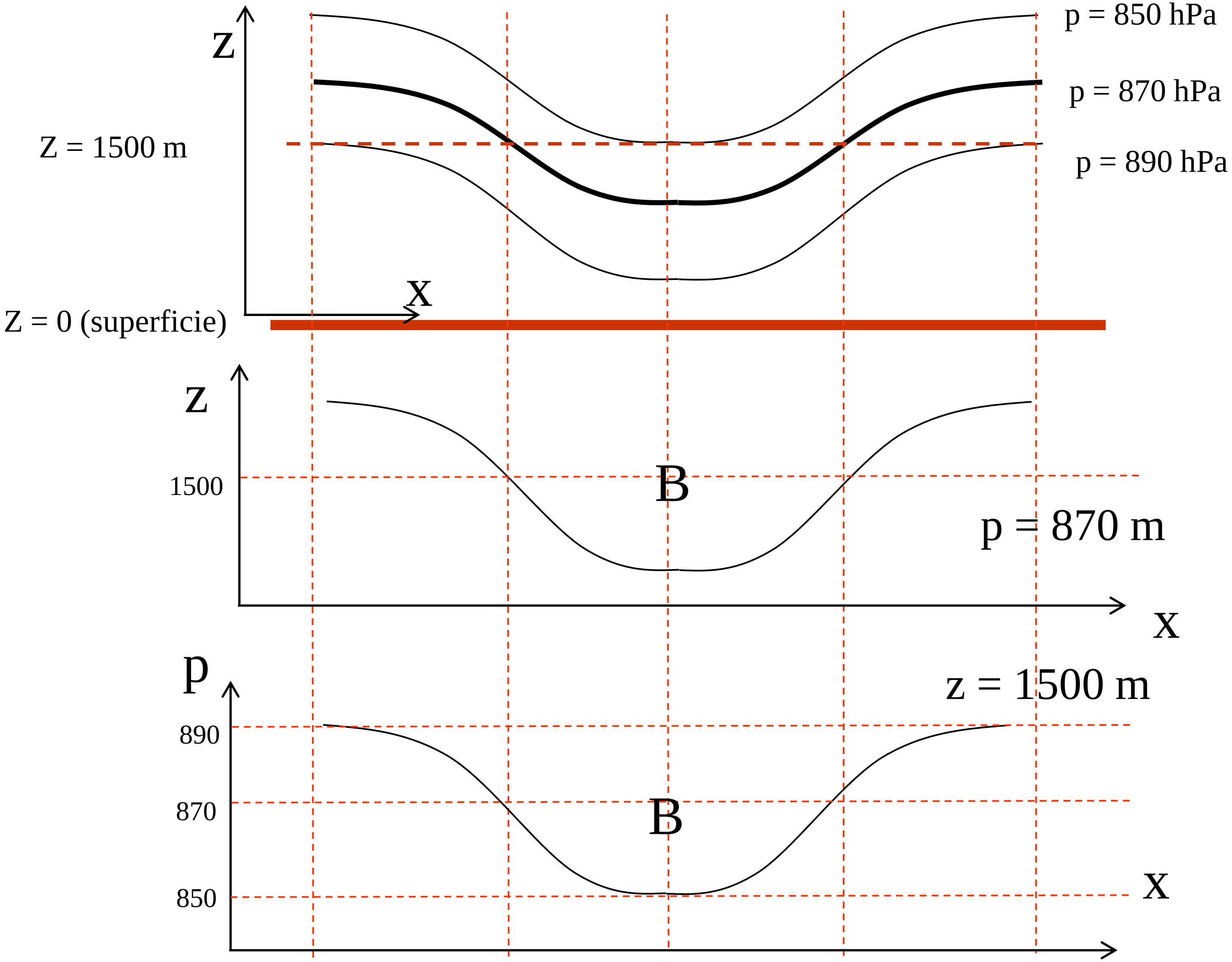
Viento solo debido a gradiente de presión
Viento Geostrofico (equilibrio FGP y Fcoriolis)
Viento real (equilibrio FGP y Fcoriolis y Froce)

Efecto de la fricción en torno a centros de A y B presión...



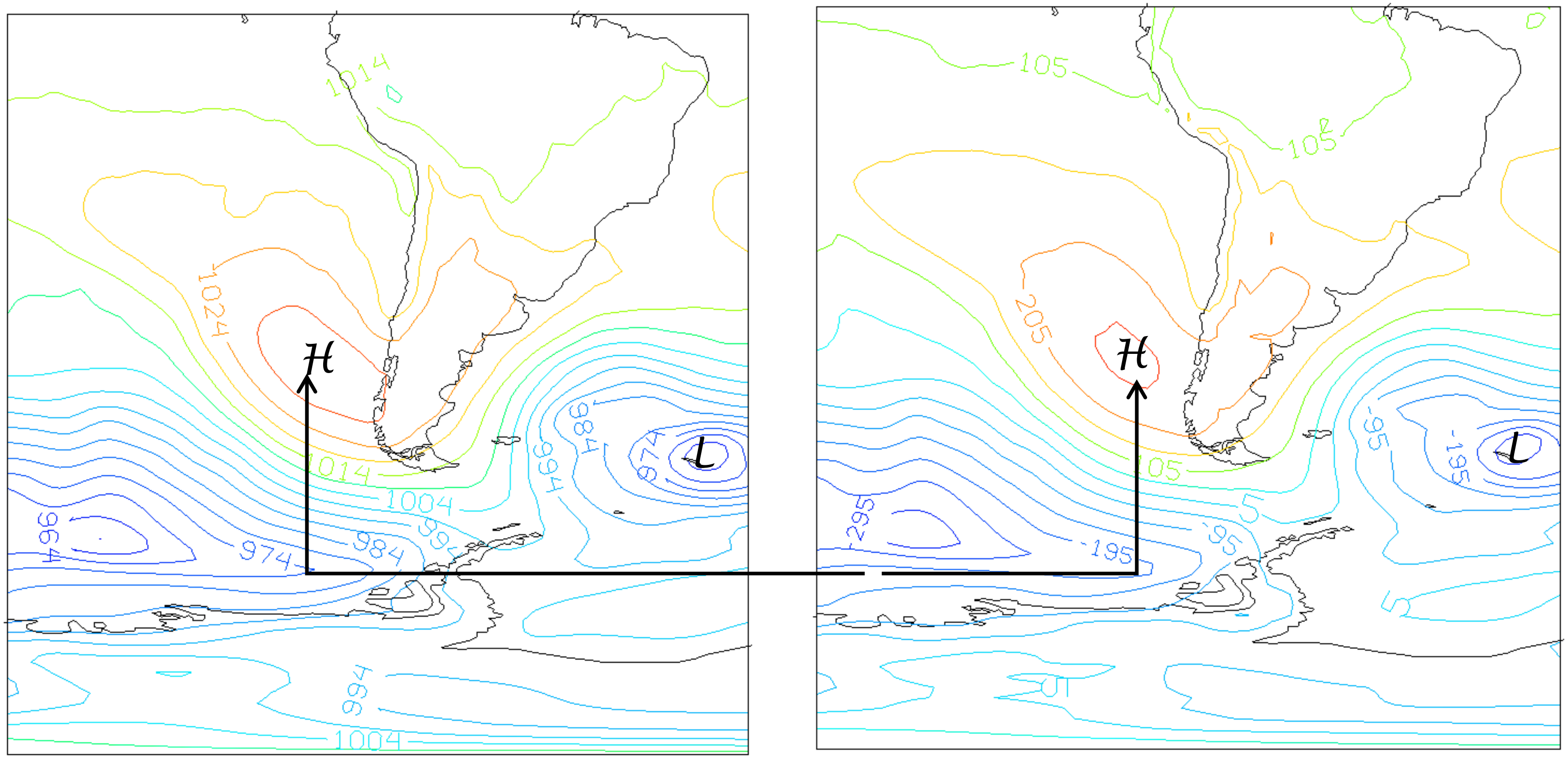


Adapted from Thurman, Harold V. **Essentials of Oceanography, 5th ed.** Prentice-Hall, Inc., 1996.

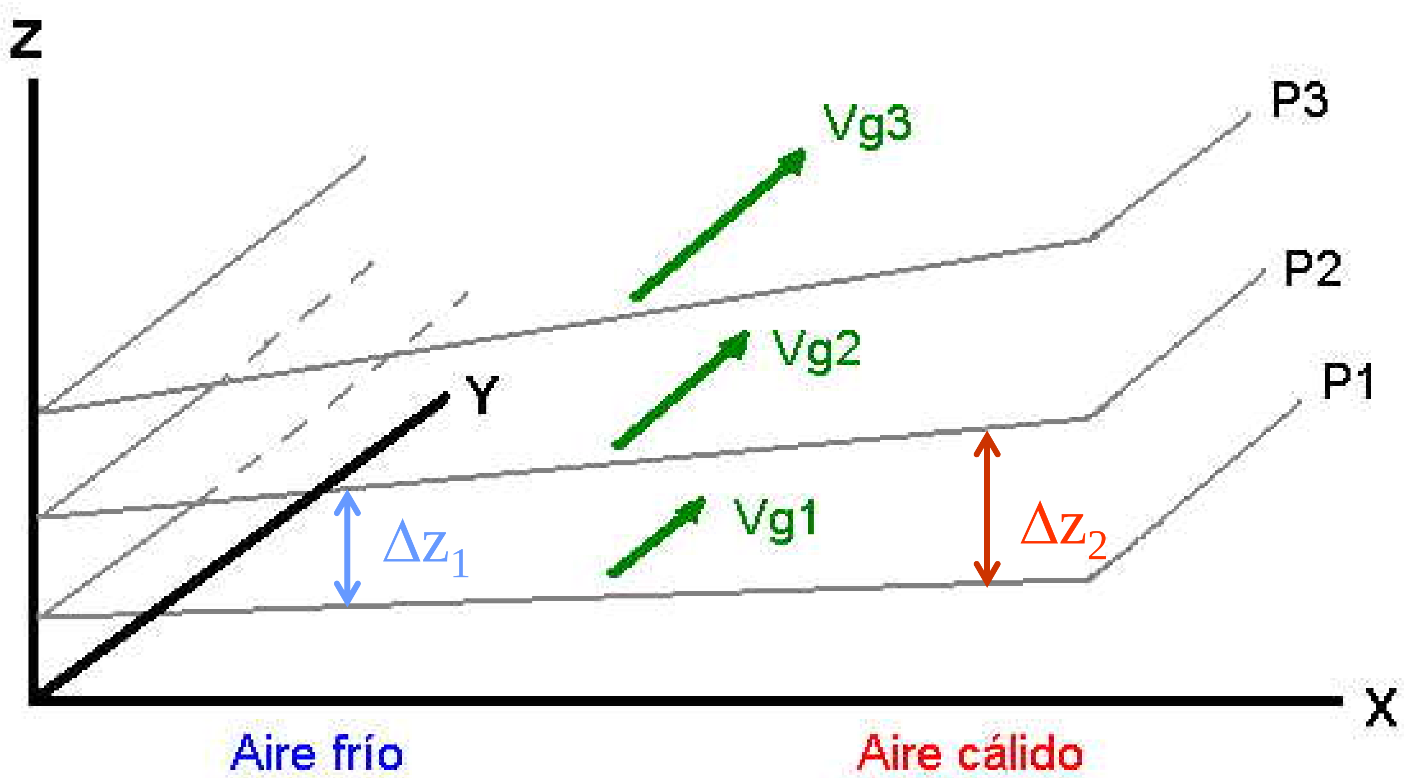

z
p = 850 hPa
p = 870 hPa
Z = 1500 m
p = 890 hPa
x
Z = 0 (superficie)
z
1500
B
p = 870 m
x
p
z = 1500 m
890
870
B
850
x

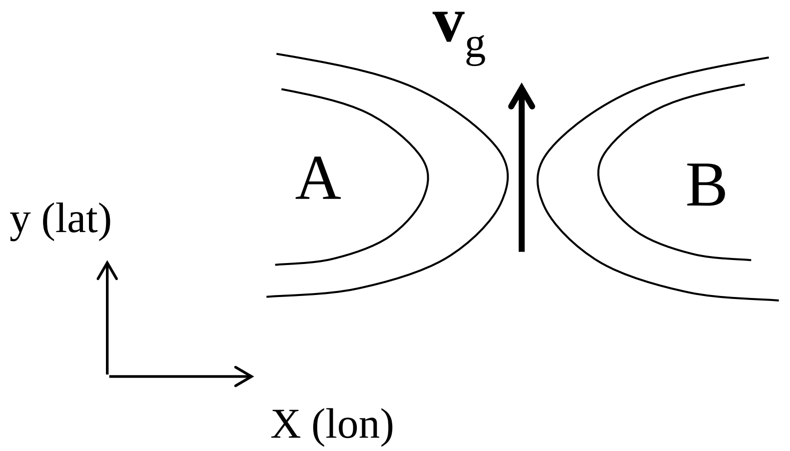
Presión @ z = 0 m (PNM)

Altura geopotencial @ p = 1000 hPa

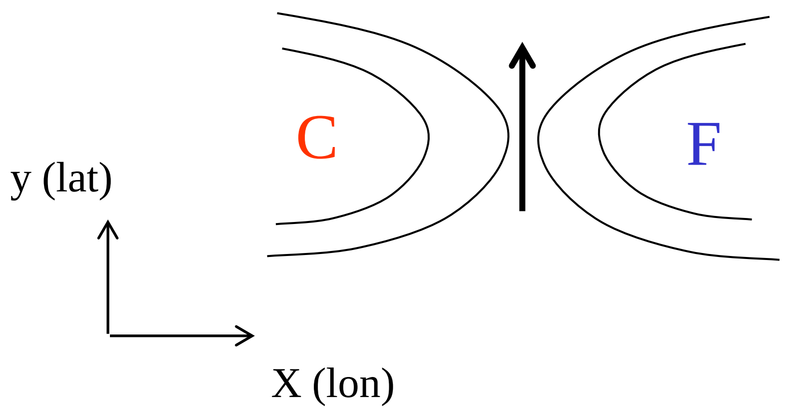


Gradiente de T, Cizalle del Viento y Viento Térmico

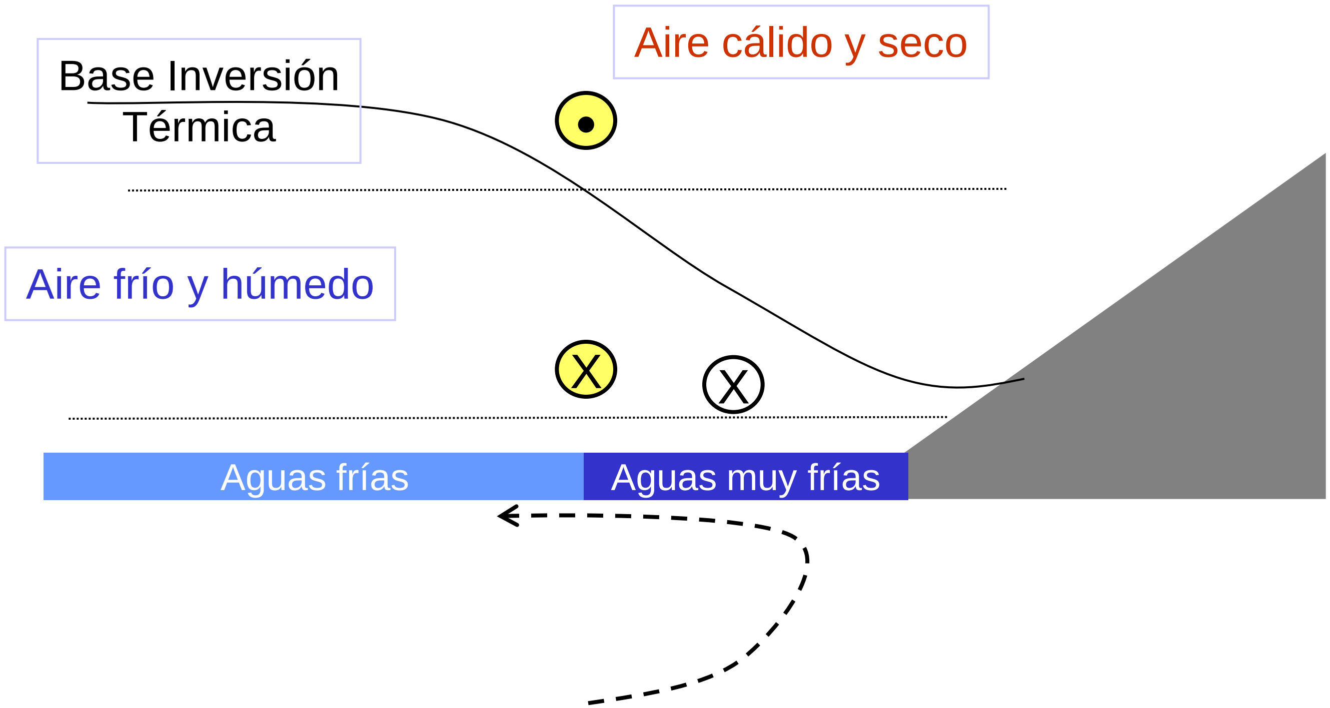


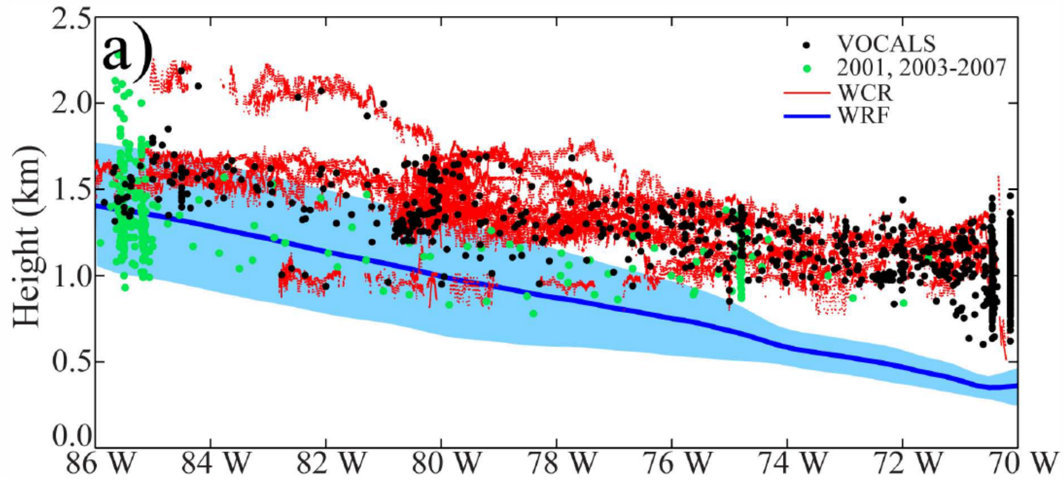


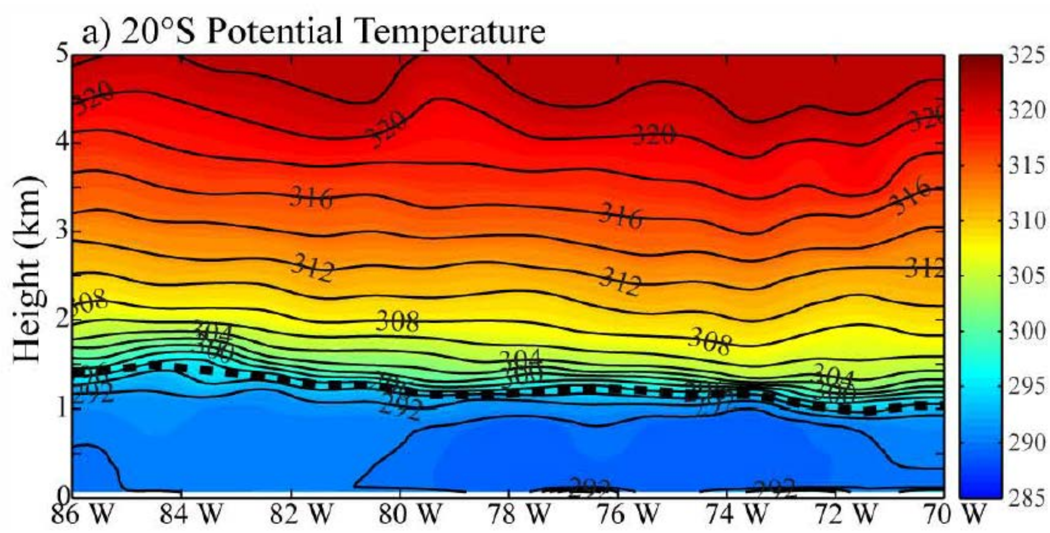
$$\mathbf{V}_T = v_g^{Sup} - v_g^{inf}$$



Aplicación cualitativa de viento térmico.
Dibuje el perfil vertical del viento meridional (v(z)) frente a la costa de Chile central. En superficie el viento es del sur. Para ello, considere la dirección del viento térmico a 50 m y 500 m



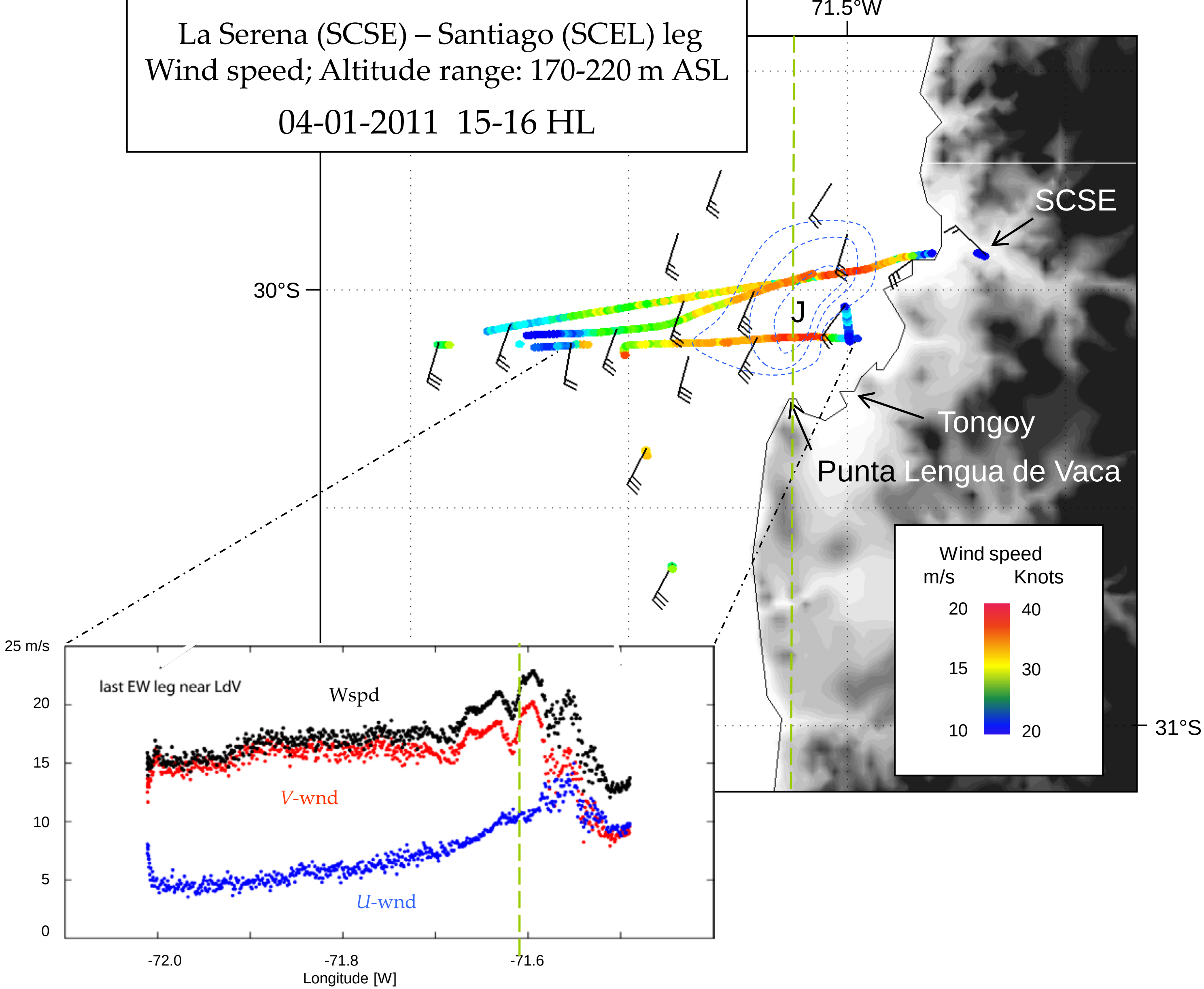

a)
VOCALS
2001, 2003-2007
WCR
WRF
Height (km)
2.5
2.0
1.5
1.0
0.5
0.0
86 W
84 W
82 W
80 W
78 W
76 W
74 W
72 W
70 W

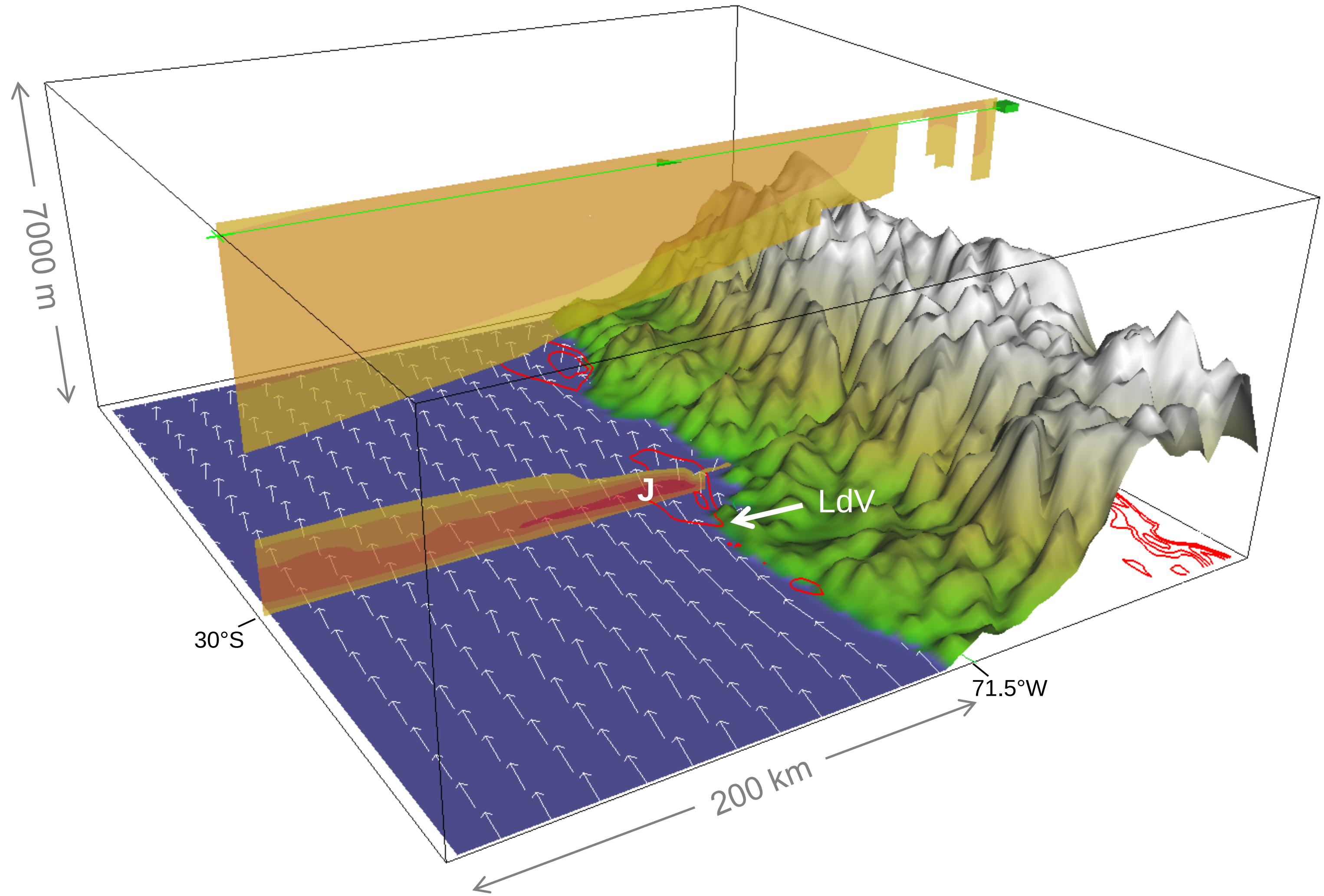

a) 20°S Potential Temperature
Height (km)
320
316
312
308
304
300
292
86 W
84 W
82 W
80 W
78 W
76 W
74 W
72 W
70 W
325
320
315
310
305
300
295
290
285

Misión Tongoy 02

La Serena (SCSE) – Santiago (SCEL) leg
Wind speed; Altitude range: 170-220 m ASL

04-01-2011 15-16 HL





7000 m
J
LdV
30°S
71.5°W
200 km