Atmospheric instability and sounding-derived indices

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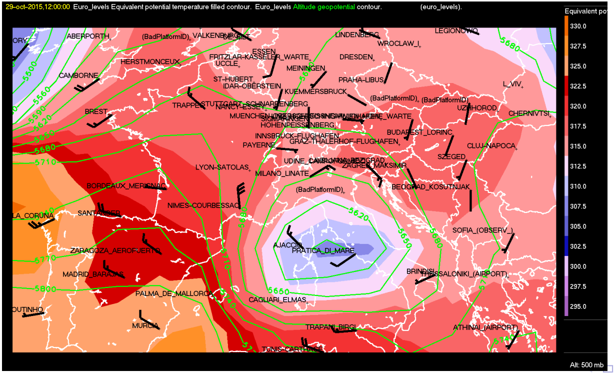
meteo.FVG

ARPA FVG - OSMER
Osservatorio meteorologico regionale

Outline

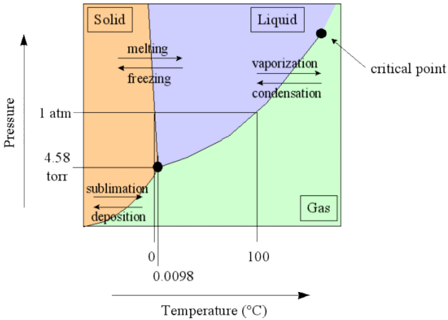
1. Basic variables and adiabatic processes.
2. Atmosphere (in)stability.
3. Radiosoundings: skew-T and Thetaplot.
4. Sounding-derived indices and their correlations.
5. Intro to forecasting meteo events with sounding-derived indices.

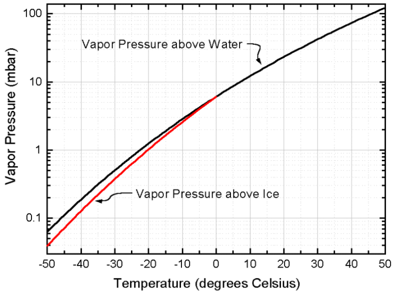


Europe at 500 hPa as seen by RDS alone (WND barbs, Z lines, Θ_e filled)

Section 1

Basic variables and adiabatic processes





Source: http://www.its.caltech.edu/˜atomic/snowcrystals/ice/ice.htm

Dry air and water vapor mixture

- Air is a *mixture* made by a variable part (0-4%) of H_2O (mass 18) plus a *fixed* proportion of other gases: 78% N_2 (mass 28), 21% of O_2 (mass 32), 0.9% of Ar, 0.03% of CO_2,...

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  1) DRY AIR: $\mathbf{p_d} = \rho_\mathbf{d} \mathbf{R_d} \mathbf{T}$, with $R_d = 286.99$ J/(kg K);
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- Air *pressure* is $\mathbf{p} = \mathbf{p_d} + \mathbf{e}$; air *density* is $\rho = \rho_\mathbf{d} + \rho_\mathbf{v} = \rho_\mathbf{d}(\mathbf{1} + \mathbf{q})$, where $\mathbf{q} = \rho_\mathbf{v}/\rho_\mathbf{d} = \mathbf{0.622}\frac{\mathbf{e}}{\mathbf{p-e}}$ is the water vapor *mixing ratio*. One can define *virtual temperature* $T_v \cong T(1 + 0.6q)$ so that $\mathbf{p} = \rho \mathbf{R_d T_v}$.

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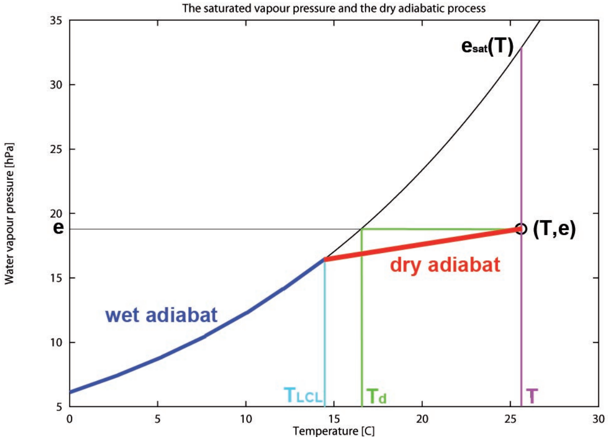
- The maximum quantity of water vapor (before condensation) depends only by air *temperature*, via the *saturation vapor pressure*, simplified by: $\mathbf{e_{sat}(T)} = \mathbf{6.11} \cdot \mathrm{e}^{\frac{\mathbf{19.8 \cdot T}}{\mathbf{T+273}}}$. *Relative humidity* is $\mathbf{RH} = \mathbf{100} \cdot \frac{\mathbf{e}}{\mathbf{e_{sat}(T)}}$. In NE Italy q varies between a minimum of 1 g/kg to a maximum of about 22 g/kg. Note that H_2O is lighter than dry air (molecular mass of 18 vs. 29): the more moist air, the less dense it is.

Saturation diagram: the point of view of water



The *dew–point temperature*, T_d, is defined implicitly on the $e_{sat}(T)$ curve as the temperature when air will become saturated conserving its initial partial pressure e, so that $\mathbf{e} = \mathbf{e_{sat}}(\mathbf{T_d})$.

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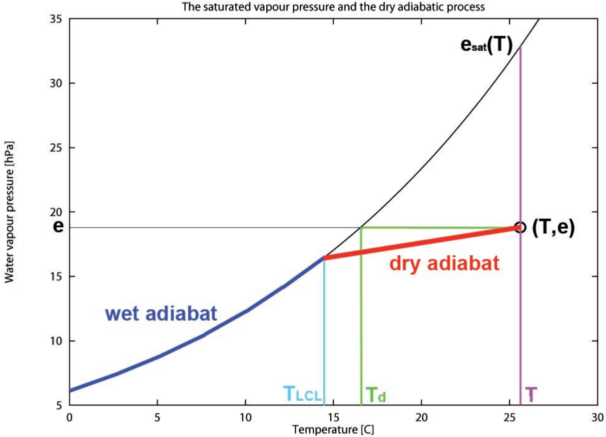

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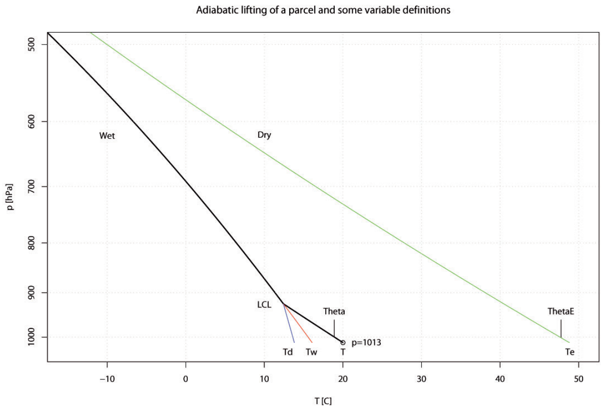
When air is lifted adiabatically, it follow a **dry** adiabat until saturation at *Lifted Condensation Level temperature*, T_{LCL}, then it follow a **wet** adiabat. Air mixture is defined by 4 variables: p, T, ρ plus a variable for humidity, like q or RH or T_d or dew-point depressure $(T - T_d)$.

The point of view of the air parcel



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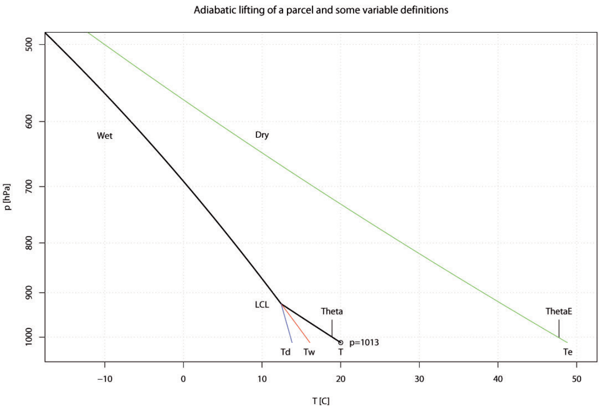

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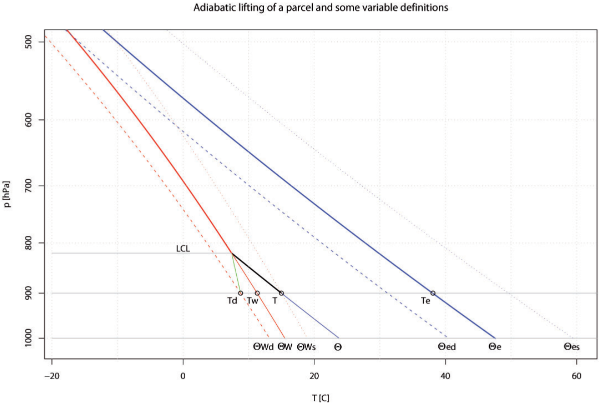
If, after LCL, it is *lifted* along a wet pseudo-adiabat until all moisture is removed ($q = 0$) and then it is sink down at the initial level through a dry adiabat, it reaches the *equivalent temperature*, T_e. “Equivalent” because it considers the warming due to the latent heat of vapor condensation.

Referring everything to a standard level



To make things more comparable, temperatures can be referred to the *standard* level (1000 hPa). Bringing the initial parcel there along a dry adiabat defines the *potential temperature*, Θ. The dry adiabat used to define T_e intersects the 1000 hPa level at the *equivalent potential temperature*, Θ_e.

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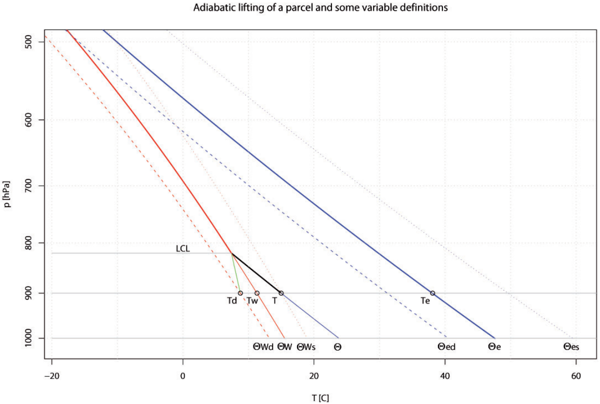

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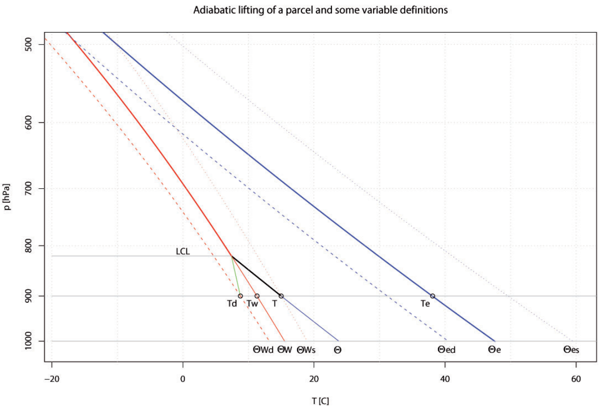

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3 transformations: potential, equivalent and wet-bulb

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    $\Theta_{ed} = \Theta_e(p, T_d, q)$, $\Theta_e(p, T, q)$ and $\Theta_{es} = \Theta_e(p, T, q_{sat})$
    (note that Θ_{es} depends only by p and T!), where (Bolton 1980):

$$\Theta_e(p, T, q) = T \cdot \left(\frac{1000}{p}\right)^{0.2854\,(1-0.28q)} \cdot \mathrm{e}^{q(1+0.81q)\left(\frac{3376}{T_{LCL}} - 2.54\right)} \quad (1)$$

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There are 3 correspondences:

$T_d \leftrightarrow \Theta_{ed} \leftrightarrow \Theta_{wd}$,
$T_w \leftrightarrow \Theta_e \leftrightarrow \Theta_w$,
$T \leftrightarrow \Theta_{es} \leftrightarrow \Theta_{ws}$.

Dry, moist and pseudo-saturated adiabatic processes

- Dry adiabatic: air is considered dry (neglecting the vapor enthalpy)

$$\text{No saturation } (q = q_0 = constant) \text{ and } c_p \cong c_{pd} = 7/2R_d \text{ (dry air is biatomic)} \tag{3}$$

$$\text{Invariant}: \Theta(T,p) = (T)\cdot\left(\frac{1000}{p}\right)^{R_d/c_{pd}} = (T)\cdot\left(\frac{1000}{p}\right)^{2/7} \tag{4}$$

$$\text{LapseRate}: \; -\frac{\mathrm{d}\,T}{\mathrm{d}\,z} = \mathbf{\Gamma_d} = \frac{\mathbf{g}}{\mathbf{c_{pd}}} \cong 9.76\,^{\mathrm{o}}\mathrm{C/km} \tag{5}$$

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- Saturated (or wet) pseudo-adiabatic: air is always saturated and condensate falls out of the lifted parcel

$$\text{saturation } q = q_{sat}(p,T), \text{ and } c_{p\,liq} \cong 0 \text{ and} c_{p\,ice} \cong 0 \quad (8)$$

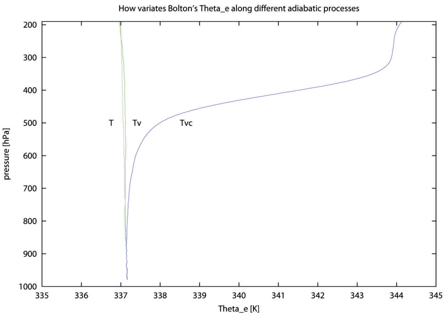
$$\text{Invariant}: \Theta_e(T,p,q) = \text{ equation(1)} \quad (9)$$

$$\text{LapseRate}: -\frac{\mathrm{d}\,T}{\mathrm{d}\,z} = \mathbf{\Gamma_s(p,q)} \cong 5 \div 8\,^{o}\mathrm{C/km} \text{ (low troposphere } \div \text{ 500 hPa)} \quad (10)$$

It is called “pseudo” because it is not reversible (rainfall).

Section 2

Atmosphere (in)stability



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4. in the simplest version (conserving Θ_e), during the saturated pseudo-adiabat the condensed water falls out, so that there is no condensate load and no latent heath of freezing.

P.S. Otherwise one could parametrize the liquid water–to–ice transition and consider the load of condensed water (which reduce buoyancy) and the latent heat of freezing (which increase buoyancy). In such a case Θ_e is not conserved and buoyancy is computed using the *virtual-cloud temperature* of the parcel, T_{vc} (see Manzato and Morgan 2003).

Parcel buoyancy

During its inviscid lifting the parcel will experience the following vertical acceleration (called Archimedes buoyancy):

$$\mathbf{B}(\mathbf{z}) = \frac{\mathrm{d}w}{\mathrm{d}t} = -\frac{1}{\rho_p} \cdot \frac{\mathrm{d}p}{\mathrm{d}z} - g = -\frac{1}{\rho_p} \cdot (-g\rho_e) - g = \mathbf{g}\frac{\rho_{\mathbf{e}}(\mathbf{z}) - \rho_{\mathbf{p}}(\mathbf{z})}{\rho_{\mathbf{p}}(\mathbf{z})} \quad (11)$$

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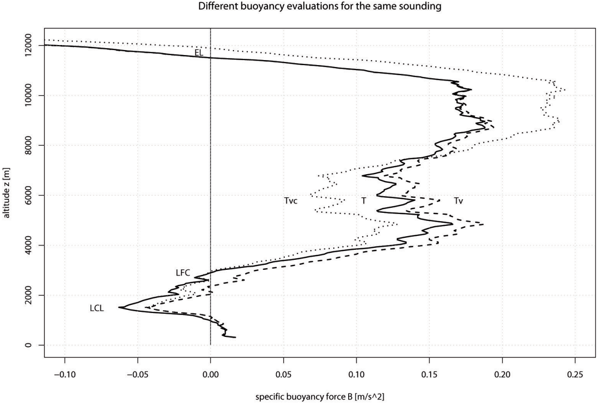
Instead, if one would consider also the vapor contribution, then he can replace the normal temperatures with the virtual temperatures (called the *"virtual correction"*), but then he should also conserve Θ_{Paluch} instead of the simpler potential temperature Θ during the "moist" adiabat... In both cases, during the saturated pseudo-adiabat it is conserved Θ_e.

The vertical profile of a parcel buoyancy and its integral



Taking a small part of environment as initial parcel and applying the Lifted Parcel Theory, it may happen that the parcel will become *buoyant* [i. e. $B(z) > 0$], from its *Level of Free Convection*, LFC, to its *Equilibrium Level*, EL.

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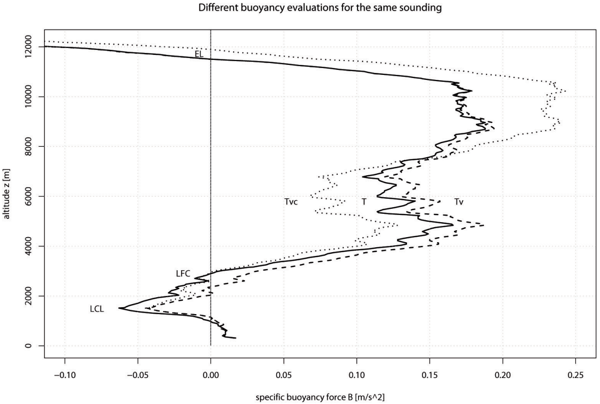

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Since $B(z) = \frac{\mathrm{d}w}{\mathrm{d}t} = w \cdot \frac{\mathrm{d}w}{\mathrm{d}z}$, integrating $B(z)$ along the vertical profile one obtains a squared vertical velocity, i. e. a kinetic energy. The *Convective Available Potential Energy*, CAPE, is obtained integrating the buoyancy from LFC to EL:

$$\mathbf{CAPE} = \int_{\mathbf{z_{LFC}}}^{\mathbf{z_{EL}}} \mathbf{B(z)} \cdot \mathrm{d}\mathbf{z} = 1/2w^2 \tag{13}$$

Potential instability

Starting from an initial level z_0 of an atmospheric profile, in case that the lifted air becomes more dense than the environment, one can think that an external agent will provide the energy (*forcing*) needed to –eventually– reach its LFC. This energy is the *Convective Inhibition*, CIN:

$$\mathbf{CIN} = \int_{\mathbf{z_0}}^{\mathbf{z_{LFC}}} \mathbf{B}(\mathbf{z}) \cdot \mathrm{d}\mathbf{z} < 0 \qquad (14)$$

Potential instability

Starting from an initial level z_0 of an atmospheric profile, in case that the lifted air becomes more dense than the environment, one can think that an external agent will provide the energy (*forcing*) needed to –eventually– reach its LFC. This energy is the *Convective Inhibition*, CIN:

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The condition that there is an initial level for which it is possible to find a LFC is *equivalent* to say that there is an initial parcel having CAPE> 0.

As we will see on the Thetaplot diagram, it is *equivalent* to say that the atmospheric profile has a low-level $\Theta_e|_{low} = \Theta_e(z_0)$ which is higher then a mid-level $\Theta_{es}|_{mid}$, i.e. MaxBuoyancy$= \Theta_e|_{low} - \Theta_{es}|_{mid} > 0$.

Static instability

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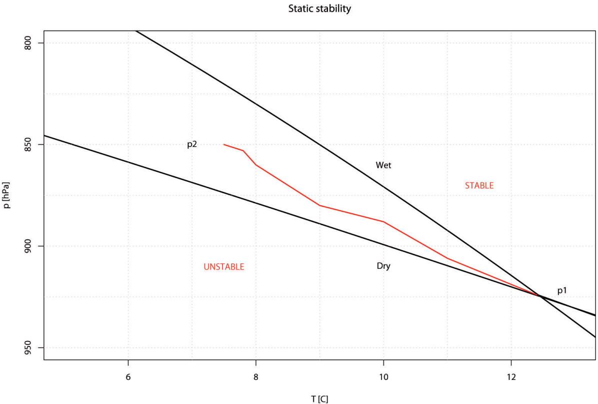
A layer of an atmospheric profile is said to be *conditionally stable* if its lapse rate is in between the dry and saturated adiabat, i. e. $\Gamma_s < \Gamma < \Gamma_d$. Lifting the bottom of the layer it will become unstable if it is saturated, but will remain stable if it follows a dry adiabat.



Potential vs. static instability

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When a layer is absolutely unstable it will be lifted even by a very small perturbation (without needs of an external forcing), so that is the "classical" instability as defined in physics. $\Gamma > \Gamma_d$ means $\frac{\mathrm{d}\,\Theta}{\mathrm{d}\,z} < 0$ and it is *no more* possible to define the Brunt-Väisälä frequency.

Section 3

Radiosoundings: skew-T and Thetaplot

Against homologation

The atmospheric profiles are usually not shown on a normal p vs. T (or z vs. T) diagram as seen until now, but are shown on specific thermodynamic diagrams. In the past many different diagrams were proposed: Neuhoff (1900), Tephigram (Shaw, 1922), Stüve (1927), Aerogram (Refsdal, 1935), Pastagram (Bellamy, 1945), skew–T (Herlofson, 1947)... Today, in 99.999% of cases it is used the skew–T diagram, but I will show you also the Theta–Plot diagram (Morgan, 1992), which I personally believe to be the most useful.

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In the approximation of *dry* air and *hydrostatic equilibrium* it is easy to derive the *hypsometric* or *thickness* equation:

$$\ln \frac{\mathbf{p_2}}{\mathbf{p_1}} = -\frac{\mathbf{g}}{\mathbf{R_d}\,\overline{\mathbf{T}(\mathbf{z})}} \cdot (\mathbf{z_2} - \mathbf{z_1}) \qquad (15)$$

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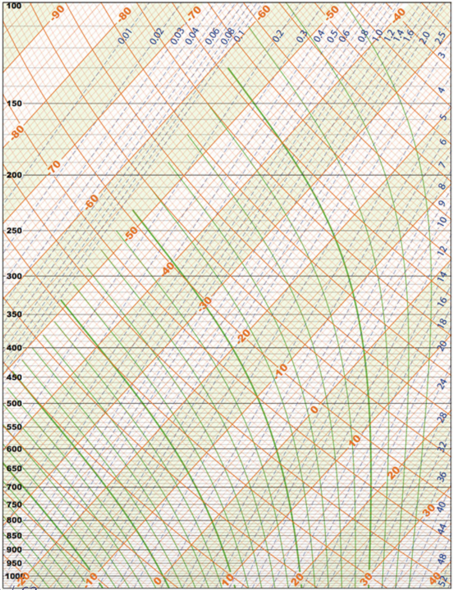
From this equation it is possible to see that the height z is approximately proportional to the opposite of the natural logarithm of pressure p. Hence, on the ordinate it will be shown $-\ln(p/1000)$.

A Skew-T chart



- On the skew-T diagram the abscissa is turned 45^o, so that isotherms are no more vertical lines, but are skewed of 45 degree to the right.

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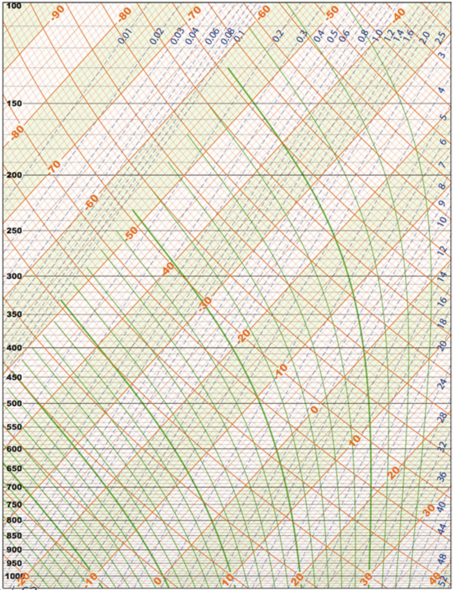

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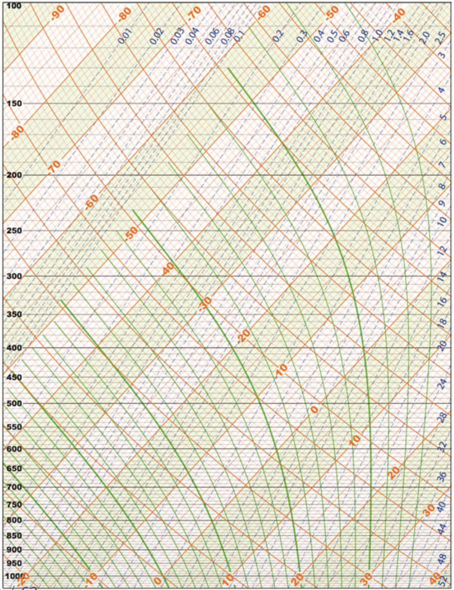

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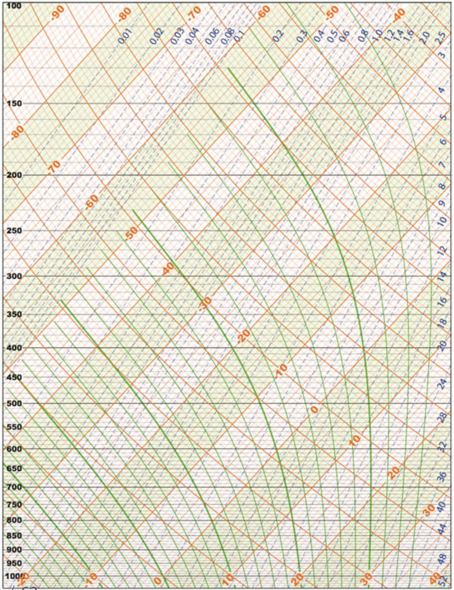

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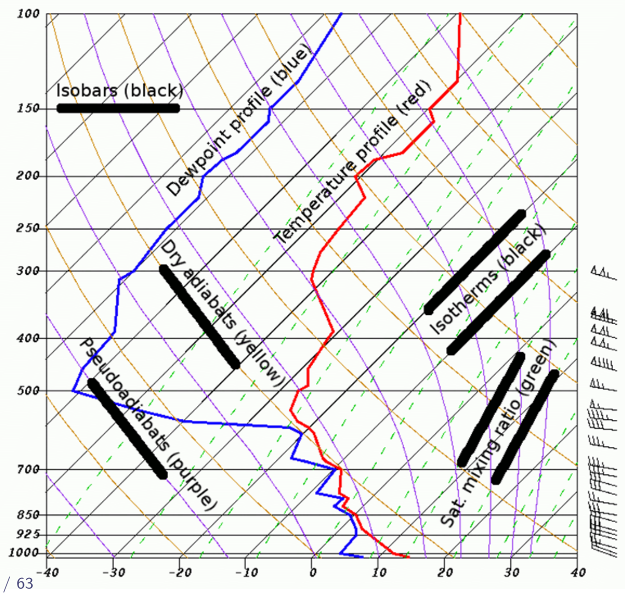
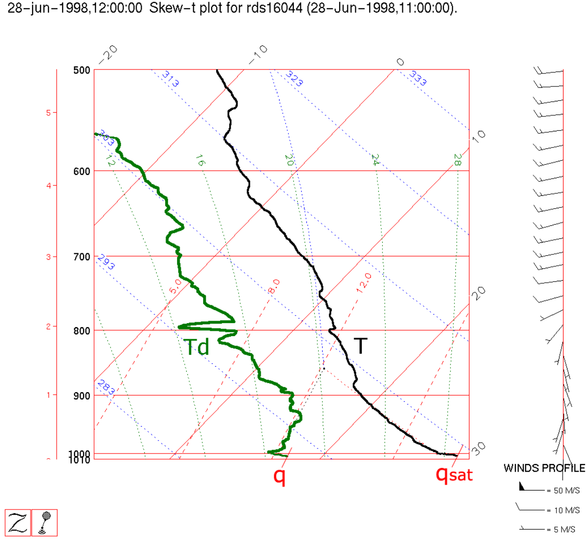
Skew-T graphical explanation



The atmosphere profile is drawn reporting at each pressure level $T(p)$ and $T_d(p)$.

Usually also the horizontal–wind profile is shown on the right side.

A potentially unstable sounding shown on a Skew-T



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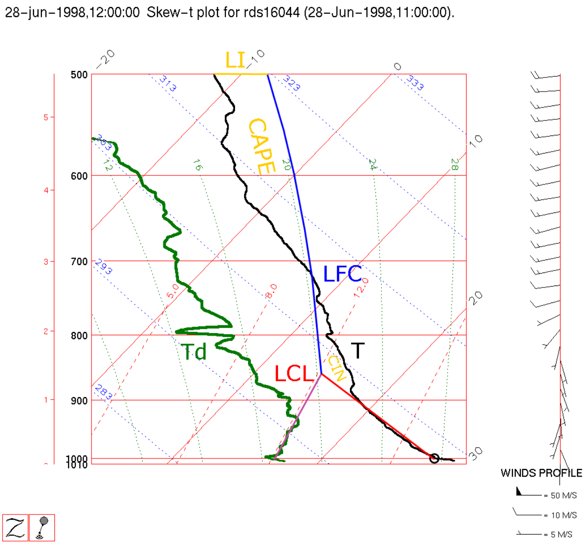

If the mean air in the lowest levels (note the superadiabatic surface) is lifted along a dry adiabat until LCL and then along a saturated pseudo-adiabat, a LFC can be found, hence CAPE>0. Note that it is needed some forcing to overtake the CIN.

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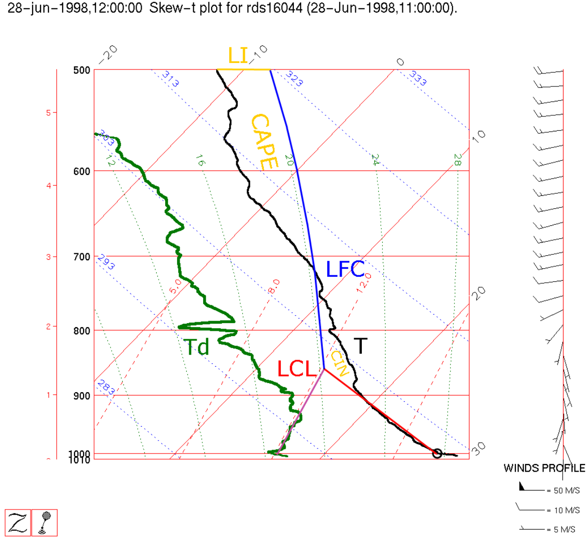

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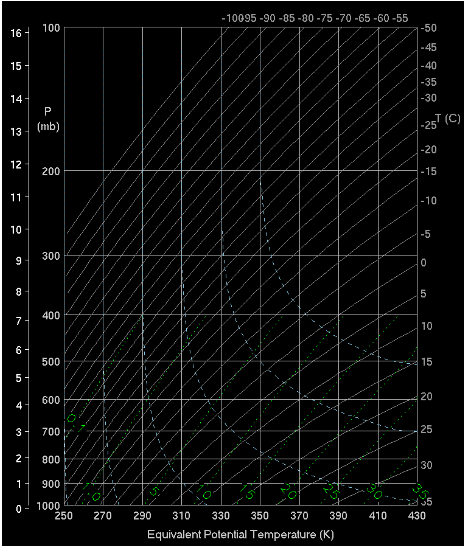
The temperature difference between the lifted parcel and the environment at $p = 500\,\text{hPa}$ is the *Lifted Index* (Galway 1956).

A Theta–plot chart (made by the NCAR “Zebra” software)



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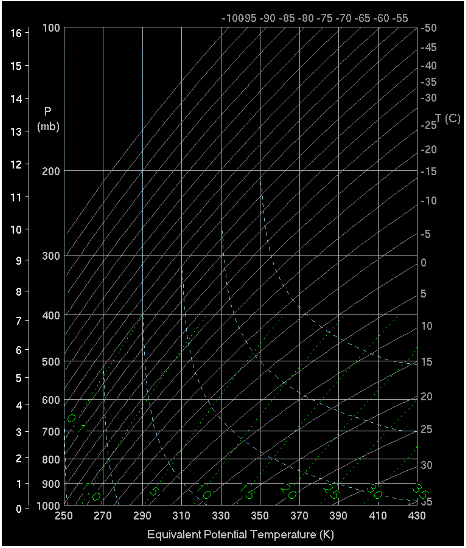

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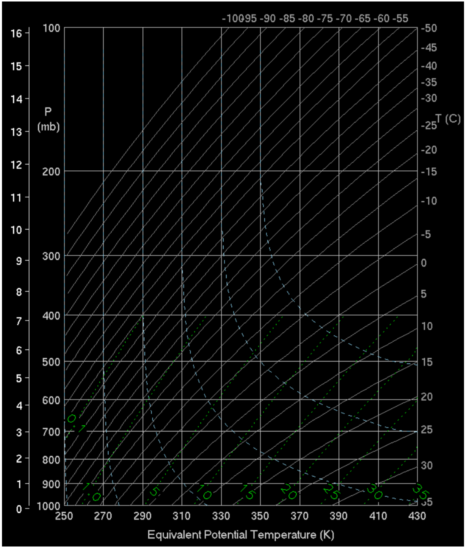

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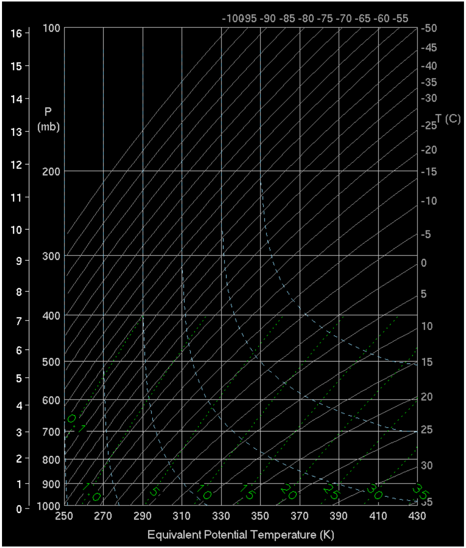

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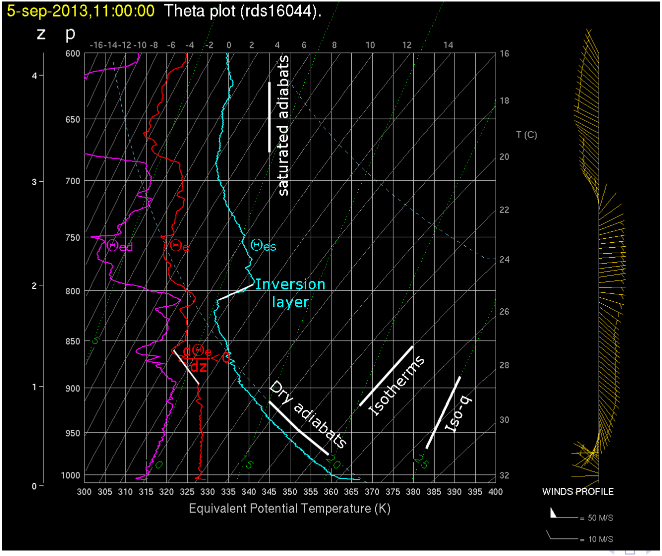
Theta-plot graphical explanation



On each level of a Theta-plot these 3 values are drawn: Θ_{ed}, Θ_e and Θ_{es}.

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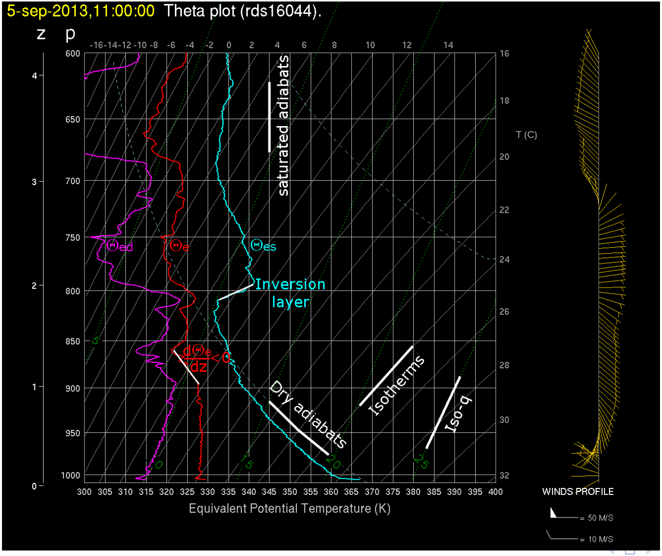
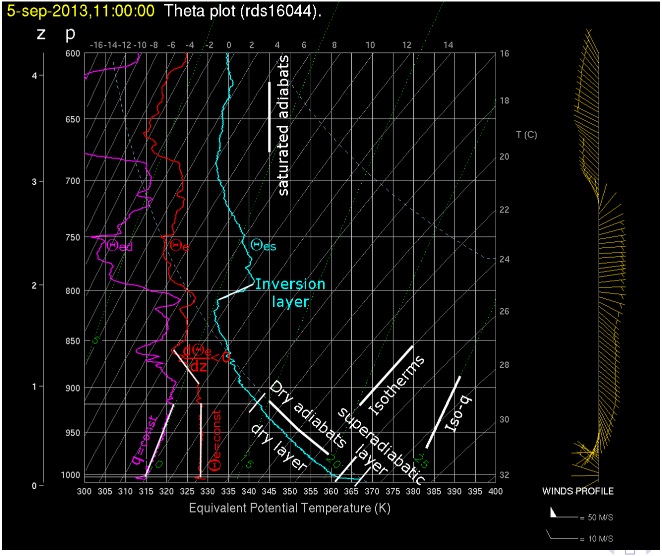


On each level of a Theta-plot these 3 values are drawn: Θ_{ed}, Θ_e and Θ_{es}. This Udine sounding, launched at 11:00 UTC of 05/09/2013, has an *inversion* layer ($\mathrm{d}T/\mathrm{d}z < 0$) at 800 hPa and also a layer where $\mathrm{d}\Theta_e/\mathrm{d}z < 0$ (between 900 and 850 hPa), but it is not *potentially unstable* (no LFC).

On Theta-plot is easy to identify where Θ_e is conserved



The "third" line of the Thetaplot shows Θ_e, that is one of the most *conserved* variables in atmosphere, since it is conserved even in *"dry layers"*, like that between 1000 and 925 hPa (q=10g/kg!).

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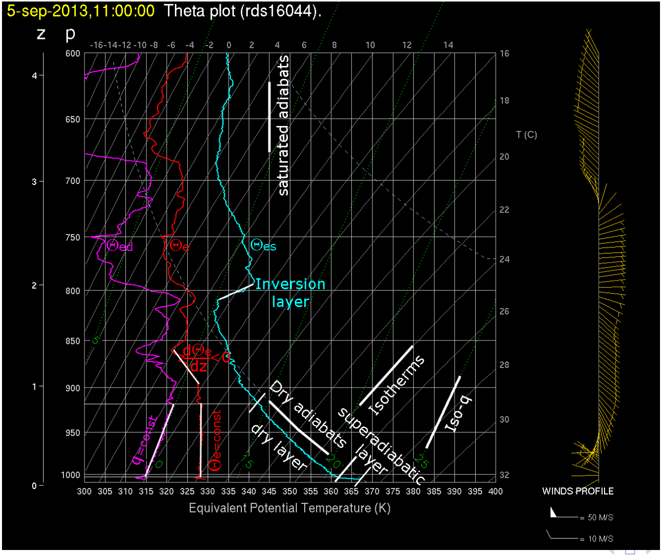

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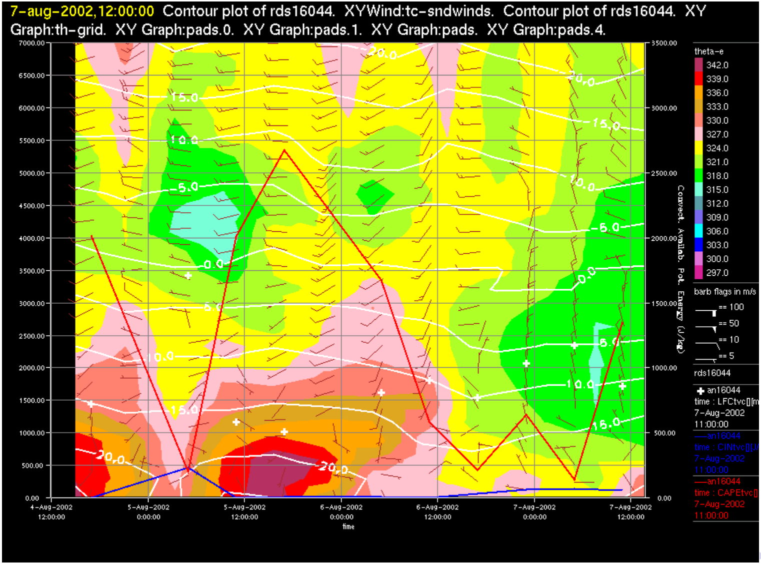
Vertical time-series of Θ_e observed by RDS every 6h



Θ_e (filled) gradients track very well the air mass changes, e.g. fronts.

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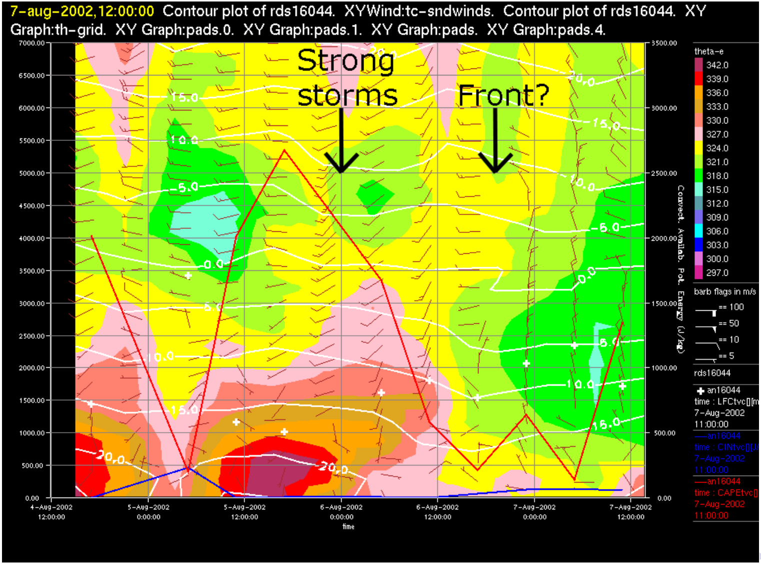
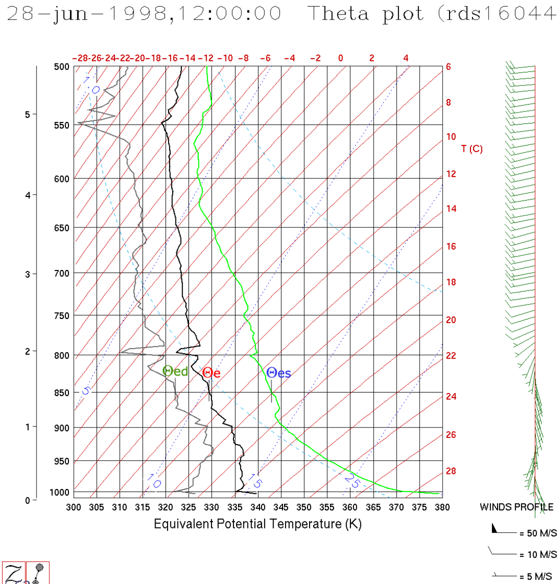


Θ_e (filled) gradients track very well the air mass changes, e.g. fronts.

Note CAPE, CIN and LFC (+).

Observed very strong storms around 00 UTC of 06/08/2002.

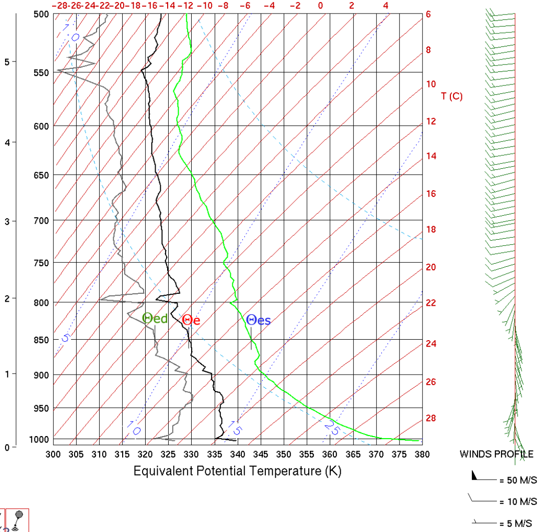
Equivalent Potential Temperatures on a Theta-plot



Operatively, the Theta-plot diagram is computed observing at different levels p, T and T_d, then deriving $q(p, T, T_d)$ and $q_{sat}(p, T)$ and lastly computing and drawing at each level $\Theta_{ed} = \Theta_e(p, T_d, q)$, $\Theta_e = \Theta_e(p, T, q)$ and $\Theta_{es} = \Theta_e(p, T, q_{sat})$.

Equivalent Potential Temperatures on a Theta-plot

28–jun–1998,12:00:00 Theta plot (rds16044).



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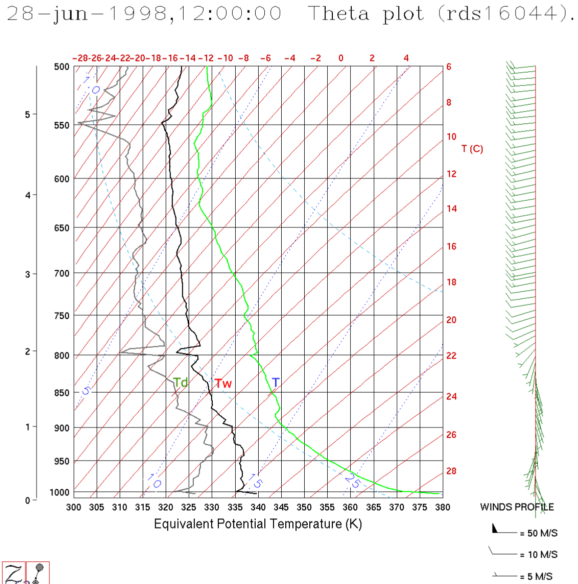
Temperatures on a Theta-plot



The vertical profiles of Θ_{ed}, Θ_e and Θ_{es} intersect on the isothermes T_d, T_w and T respectively, because of the correspondences seen before. Example shows temperatures at 850 hPa. $(\Theta_{es} - \Theta_{ed})$ resembles the dew-point depressure $(T - T_d)$: the more distant are these two lines, the more dry is that level.

Temperatures on a Theta-plot

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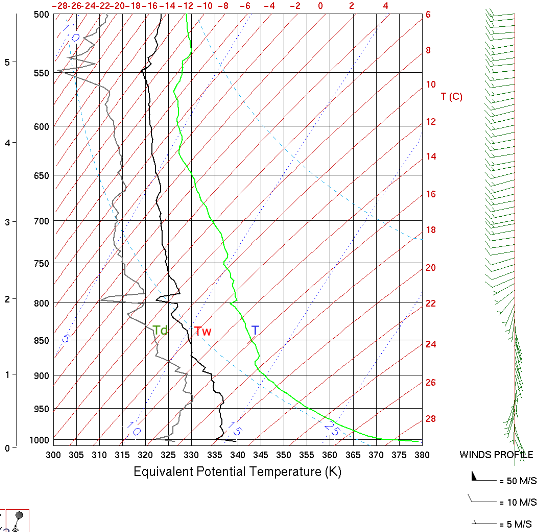

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Mixing ratios on a Theta-plot

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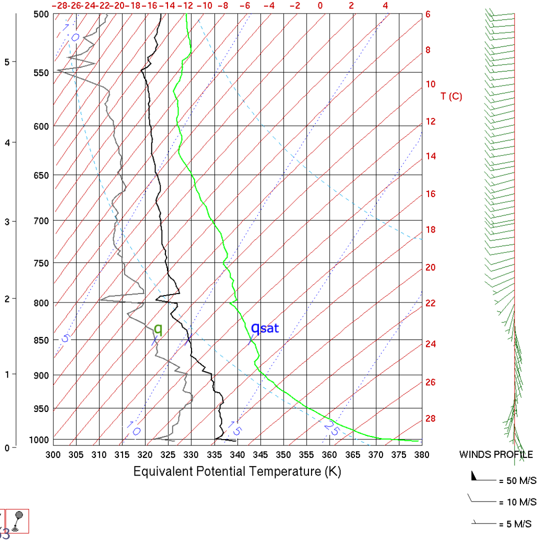

The vertical profiles of Θ_{ed} and Θ_{es} intersect on the iso-mixing ratio lines ($q = const$) q and q_{sat}, respectively.

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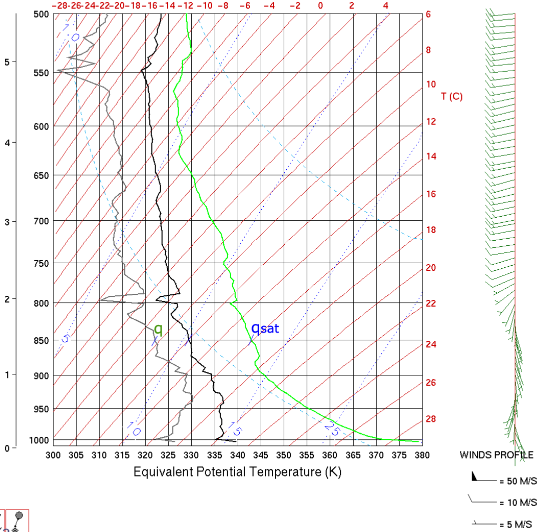
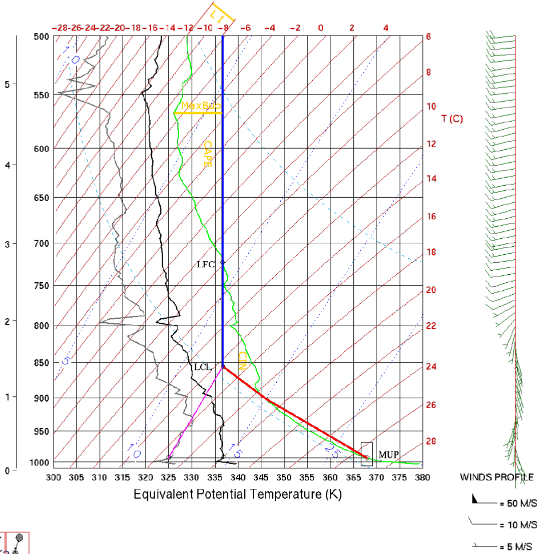


The vertical profiles of Θ_{ed} and Θ_{es} intersect on the iso-mixing ratio lines ($q = const$) q and q_{sat}, respectively.

The sounding shown is the Udine RDS launched at 11:00 UTC of 28/06/1998. Note that soundings are launched before their nominal "time" because the ascension takes about 45 minutes.

A potentially unstable sounding shown on a Theta-plot

28-jun-1998,12:00:00 Theta plot (rds16044).



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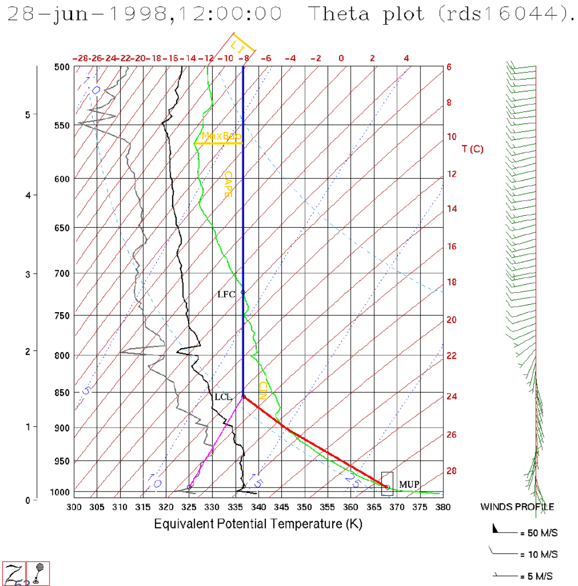
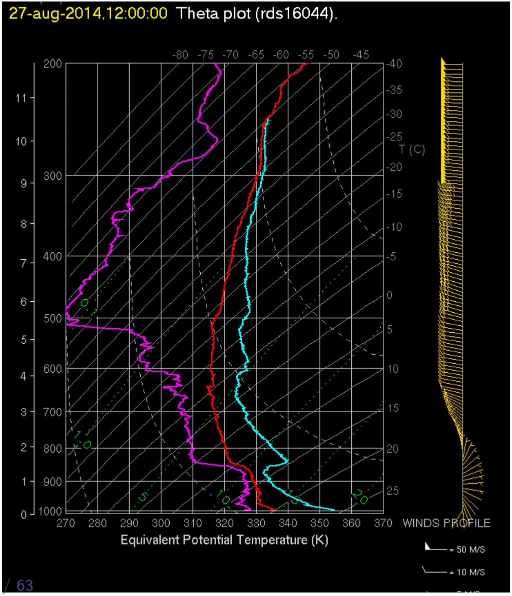


If the mean air in the lowest levels (avoiding the surface superadiabatic overestimation) is lifted along a dry adiabat until LCL and then along a vertical saturated pseudo-adiabat, a LFC can be found, hence CAPE>0. Since Θ_e is conserved along the whole process, the LFC exists *if and only if* Θ_e of the initial parcel is higher then the lowest Θ_{es} in the mid-levels, i. e. MaxBuo>0.

The Lifted Parcel Theory on a Theta-plot



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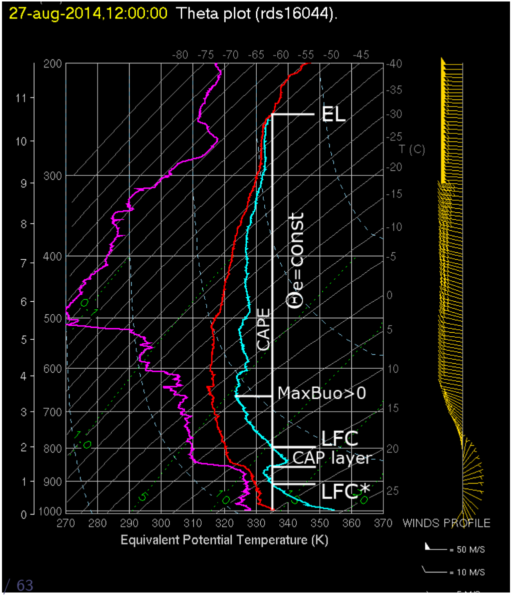

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In this case there is a first LFC*, followed by a *capping layer*, CAP. Specifically, it is an *inversion*, but in general it is sufficient to have a layer where $\mathrm{d}\Theta_{es}/\mathrm{d}z > 0$ and not also $\mathrm{d}T/\mathrm{d}z > 0$, because an increase of Θ_{es} with z can stop the rising parcel.

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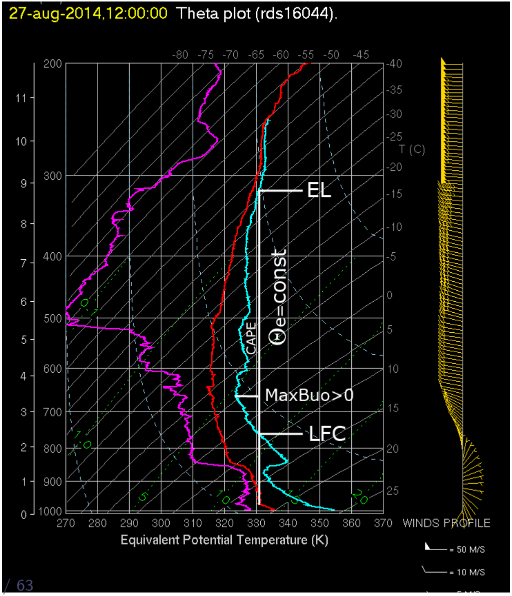

Choosing another *initial parcel* means simply to start from a different Θ_e and to draw another vertical line. It is immediate to see how LFC and EL change and how much are reduced the CAPE energy and the MaxBuo.

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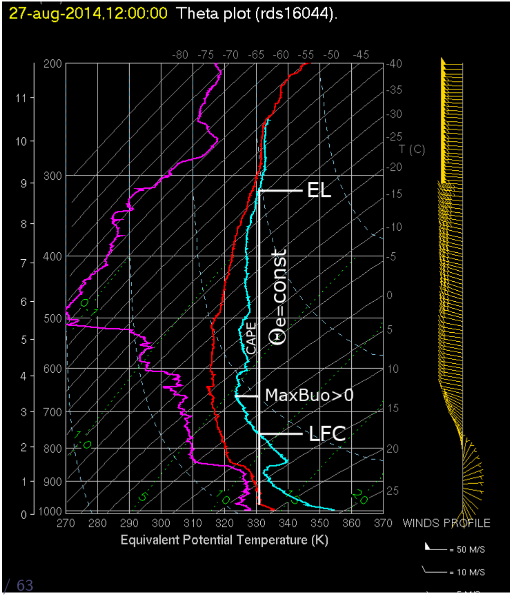
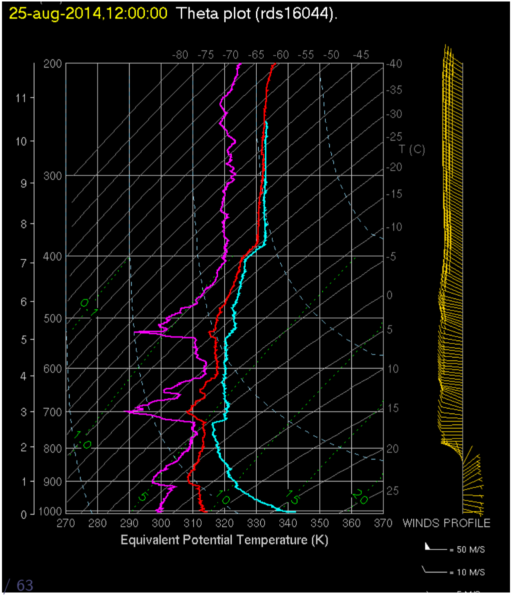


Choosing another *initial parcel* means simply to start from a different Θ_e and to draw another vertical line. It is immediate to see how LFC and EL change and how much are reduced the CAPE energy and the MaxBuo.
On the Thetaplot the *Most Unstable Parcel* (MUP) is simply identified as the level having the maximum Θ_e among all the low levels.
The choice of the initial level determines everything about the whole adiabatic lifting.

A potentially stable sounding having $d\Theta_e/dz < 0$



If Θ_e is always lower than Θ_{es} then it is not possible to find a LFC, hence CAPE $= 0$ and MaxBuo< 0. It is better to have a variable defined even for stable soundings (like MaxBuo or LI) than a *bounded* variable like CAPE.

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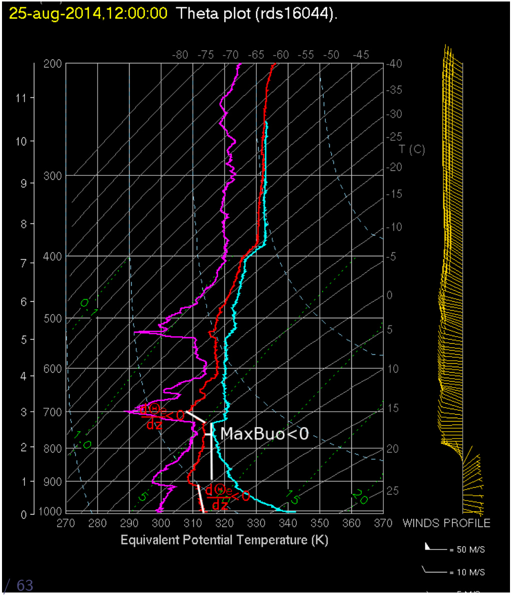

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Importance of low-levels Θ_e

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- That is true when buoyancy is computed using the normal temperature. If the virtual correction is used, then there is a –*very small*– influence of the environmental humidity profile even above the initial parcel level.

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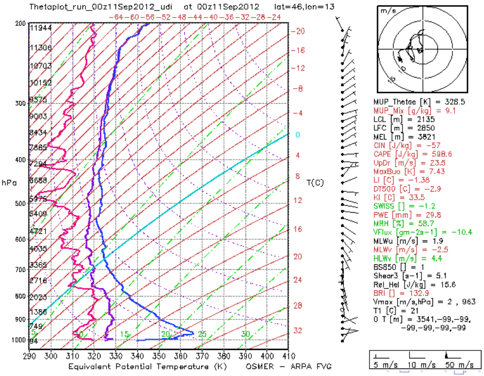
6. The Theta-plot show also T_w and not only T and T_d.

Make your choice!

Section 4

Sounding-derived indices and their correlations



Data-mining: the human effort to simplify Nature

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- Manzato and Morgan (2003) and Manzato (2003) have presented the SOUND_ANALYS.PY software to compute $\sim$ 50 indices from a high-vertical resolution sounding.

Comparing the raw data with the GTS-TEMP format

20150704_12_Udine_original.txt - Blocco note

File Modifica Formato Visualizza ?

616	44	4604	1319	93	2015	0704	1100	J2923862	RS92-SGP
TIME	HEIGHT	PRESS	T	RH	Td	Wdir	Wspd	Code	
0	93	10110	310	44	174	179	38	TUDFV	
1	103	10099	304	45	172	178	38	TI	
2	111	10090	300	46	171	178	39	TI	
3	117	10084	297	46	168	177	39	TI	
4	122	10077	294	45	164	177	39	100	
5	128	10071	291	45	160	176	40	100	
6	133	10065	289	45	159	175	40	100	
7	138	10060	288	46	159	175	41	100	
8	142	10055	287	46	161	174	41	T	
9	147	10050	287	47	162	174	41	100	
10	151	10045	286	47	163	173	41	100	
11	155	10040	286	48	164	172	42	100	
12	160	10034	286	48	165	172	42	100	
13	165	10028	285	48	166	171	42	100	
14	171	10023	284	49	166	171	42	100	
15	175	10017	284	49	166	170	42	100	
16	181	10011	283	49	166	169	42	100	
17	187	10004	283	49	166	169	42	100	
18	194	9996	282	49	166	168	42	100	
19	202	9987	281	50	167	168	41	100	
20	209	9979	281	50	167	167	41	100	
21	216	9971	280	50	168	167	41	100	
22	223	9964	280	51	168	167	40	100	
23	229	9957	279	51	169	166	40	100	
24	235	9950	279	51	169	166	39	100	
25	241	9943	278	51	169	165	39	100	
26	247	9936	278	51	169	165	39	200	
27	253	9930	277	52	169	165	38	200	
28	259	9923	276	52	168	164	38	200	
29	266	9916	276	52	168	164	37	200	
30	273	9908	275	52	169	164	36	200	
31	280	9900	275	52	169	163	36	200	
32	286	9893	274	53	169	163	35	200	
33	292	9887	274	53	169	163	35	200	
34	297	9880	273	53	169	162	34	200	
35	303	9874	273	53	169	162	34	200	
36	309	9867	272	53	169	161	33	200	
37	315	9860	272	53	168	161	33	200	
38	321	9854	271	53	168	160	32	200	
39	327	9848	271	53	168	160	32	200	
40	333	9841	270	54	169	159	31	200	
41	338	9835	270	54	170	158	31	200	
42	344	9829	270	54	171	158	30	200	
43	349	9823	270	55	172	157	30	200	
44	355	9817	270	55	172	156	29	200	
45	361	9810	269	55	172	155	29	200	
46	367	9803	269	55	171	154	28	200	
47	373	9796	268	55	170	153	28	200	
48	379	9790	267	55	170	151	27	200	
49	385	9783	266	55	168	150	27	200	
50	390	9777	265	55	166	149	26	200	
51	395	9772	264	55	165	148	26	200	
52	400	9767	263	55	165	147	25	200	
53	405	9761	263	55	165	146	25	200	

weather.uwyo.edu/cgi-bin/sounding?region=europe&TYPE=TEXT%3ALIST&YEAR=2015&MON

16044 LIPD Udine Observations at 12Z 04 Jul 2015

PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1011.0	94	31.0	17.0	43	12.20	180	7	303.2	339.7	305.4
1005.0	147	28.6	15.6	45	11.21	175	8	301.3	334.6	303.4
1000.0	191	28.2	16.2	48	11.71	170	8	301.4	336.1	303.5
925.0	876	21.6	15.6	69	12.19	165	8	301.4	337.5	303.6
868.0	1425	17.2	12.3	73	10.46	297	3	302.3	333.6	304.2
865.0	1454	17.6	11.6	68	10.01	304	2	303.1	333.1	304.9
850.0	1604	16.8	9.8	63	9.02	340	1	303.7	331.0	305.4
837.0	1735	16.2	8.2	59	8.21	344	3	304.4	329.4	305.9
809.0	2025	17.2	2.2	37	5.57	352	7	308.5	326.0	309.5
781.0	2323	15.2	-0.2	35	4.84	0	12	309.4	324.8	310.3
744.0	2734	12.4	-3.6	33	3.96	4	16	310.7	323.5	311.5
700.0	3241	8.6	-15.4	17	1.66	10	22	312.0	317.6	312.3
681.0	3463	6.8	-17.6	16	1.42	10	24	312.5	317.4	312.8
659.0	3728	4.8	-20.1	14	1.18	15	22	313.1	317.2	313.3
624.0	4168	1.3	-24.4	13	0.85	0	14	314.1	317.1	314.2
595.0	4552	-1.7	-28.1	11	0.64	15	18	314.9	317.1	315.0
573.0	4856	-4.1	-31.1	10	0.50	3	20	315.4	317.3	315.6
558.0	5064	-4.9	-40.5	4	0.20	355	22	316.9	317.7	316.9
547.0	5220	-5.5	-47.6	2	0.10	10	23	318.0	318.4	318.0
537.0	5365	-6.1	-54.1	1	0.05	7	22	319.0	319.2	319.0
509.0	5781	-8.5	-55.8	1	0.04	0	20	321.0	321.1	321.0
500.0	5920	-9.3	-56.3	1	0.04	5	19	321.6	321.8	321.6
498.0	5951	-9.3	-53.3	1	0.05	7	19	322.0	322.2	322.0
485.0	6152	-11.1	-50.2	2	0.08	20	19	322.2	322.6	322.3
432.0	7031	-18.9	-36.9	19	0.38	1	22	323.1	324.6	323.2
418.0	7275	-20.8	-33.0	33	0.57	355	23	323.8	325.9	323.9
406.0	7491	-22.5	-29.5	53	0.82	358	22	324.3	327.3	324.4
400.0	7600	-23.1	-32.1	44	0.65	0	21	324.9	327.3	325.0
397.0	7655	-23.5	-38.5	24	0.35	0	21	325.1	326.4	325.1
384.0	7897	-25.3	-40.3	23	0.30	0	21	325.8	327.0	325.9
333.0	8909	-33.9	-42.9	40	0.26	0	21	327.6	328.6	327.6
326.0	9057	-34.9	-47.9	25	0.15	0	21	328.2	328.8	328.2
317.0	9251	-36.3	-43.3	48	0.26	0	21	328.9	329.9	328.9
308.0	9450	-37.5	-53.5	17	0.09	0	21	329.9	330.3	329.9
300.0	9630	-38.9	-53.9	19	0.08	0	21	330.4	330.8	330.4
293.0	9792	-40.3	-58.3	13	0.05	2	23	330.7	330.9	330.7
281.0	10077	-42.5	-67.5	5	0.02	5	26	331.5	331.6	331.5
280.0	10101	-42.7	-67.2	5	0.02	5	26	331.6	331.6	331.6
252.0	10807	-48.3	-59.3	27	0.05	10	14	333.4	333.6	333.4
250.0	10860	-48.7	-58.7	30	0.06	10	14	333.5	333.8	333.5
247.0	10939	-49.1	-59.1	30	0.05	7	14	334.1	334.3	334.1
227.0	11486	-52.9	-66.9	17	0.02	343	12	336.4	336.5	336.4
217.0	11774	-55.5	-63.5	36	0.03	330	11	336.8	336.9	336.8

The first $\sim$ 50 levels in a raw sounding (left) or TEMP format (right).

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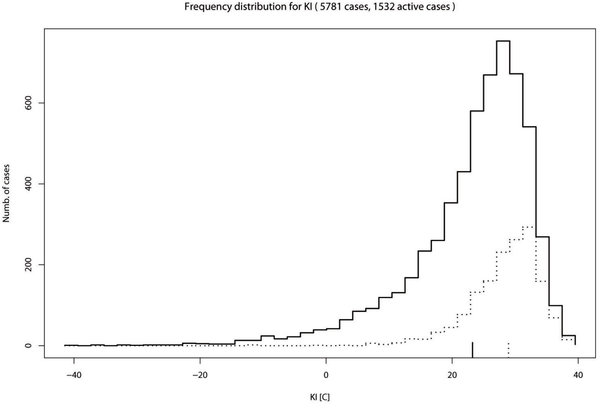
3. *Mixed indices*, which typically uses instability indices together with wind information. Very commonly used are: Energy-Helicity Index (EHI), SWEAT, SWISS...

We will see only a few of them!

K–Index and its 1995-2002 distribution above Udine



One of the oldest indices is the K–Index (George, 1960). The dot line is the sub-sample for soundings associated with convective activity in the FVG plain in the 6 hours after launch (1995-2002). Values above 25 are often associated with lightning occurrences.

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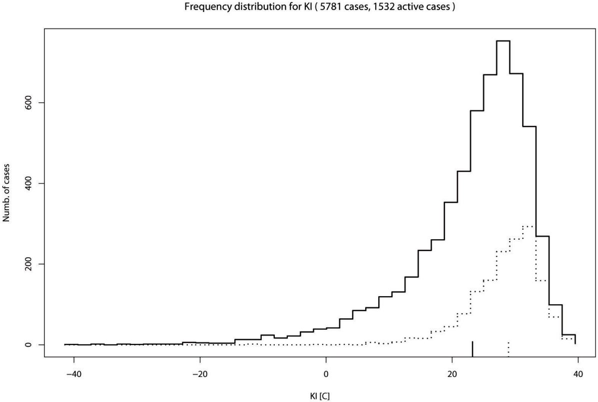

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$$\mathrm{KI} = T_{@850} - T_{@500} + T_{d\,@850} - (T_{@700} - T_{d\,@700}). \quad (16)$$

KI is defined using only environmental temperature and dew-point depressure on three mandatory levels. Even if very simple, it is also correlated to rainfall intensity.

"Two-levels" potential instability family

- *Showalter* (1953) was the first to use the difference of temperature between the lifted parcel and the environmental air at 500 hPa:

$$\mathrm{ShowI} = T_{e\,@500} - T_{p\,@500} \qquad [K] \qquad (17)$$

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- Nowadays the most used "lifted index" is the one using as initial parcel the Most Unstable Parcel (maxΘ_e), called DT500 in Manzato (2003) or MULI by many authors.

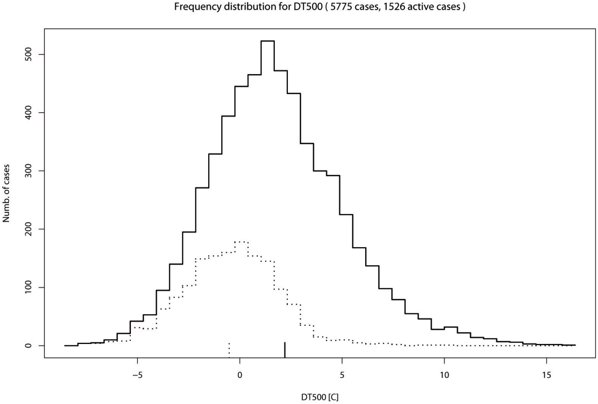
"Two-levels" potential instability family

- *Showalter* (1953) was the first to use the difference of temperature between the lifted parcel and the environmental air at 500 hPa:

$$\text{ShowI} = T_{e\,@500} - T_{p\,@500} \qquad [K] \tag{17}$$

  Showalter used as initial parcel the mean air at 850 hPa.
- Galway (1956) defined the *Lifted Index* (LI) in the same way, but using as initial parcel the mean air of the lowest 500 m.
- Nowadays the most used "lifted index" is the one using as initial parcel the Most Unstable Parcel (maxΘ_e), called DT500 in Manzato (2003) or MULI by many authors.
- Manzato (2003) introduced also the temperature difference between environment and lifted parcel evaluated at a fixed *parcel temperature* (chosen -15^{o}C) instead than to a fixed pressure level (500 hPa). It was called Difference of Temperature at the Core Level (DTC).

1995-2002 distribution of the Udine MULI



The dot distribution is the sub-sample for soundings associated with convective activity in the FVG plain in the 6 hours after launch (1995-2002). *Low* ($< 2^{o}$C) or *negative* values are associated with lightning occurrences.

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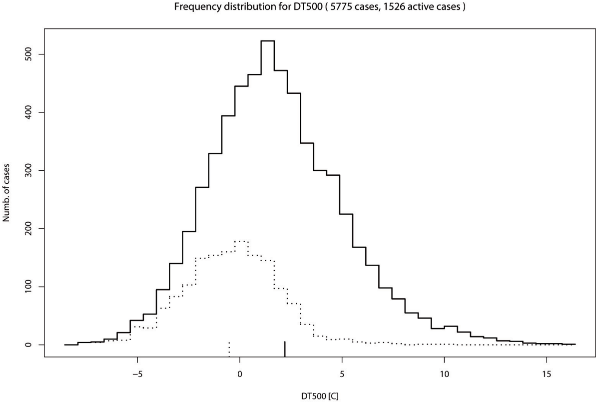

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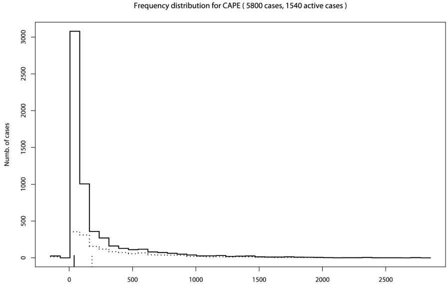
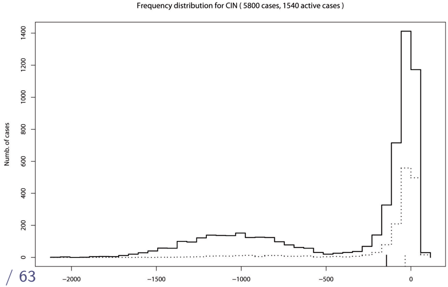
At least in Europe, there are a number of evidences where the Most Unstable Lifted Index gives better *statistical performances* when forecasting convection (lightnings or hail or storm occurrences) than CAPE, which is a bounded variable. References includes Manzato (2003), Groenemeijer and van Delden (2007), Kunz (2007)...

1995-2002 distribution of the Udine CAPE and CIN





Differently from the "two-level" instability indices (which includes also MaxBuo), CAPE and CIN are *integrated* measures of buoyancy (positive for CAPE and negative for CIN). Note that SOUND_ANALYS.PY computes the maximum UpDr velocity using only the CAPE integrated up to the parcel level of -15^{o}C instead of EL.

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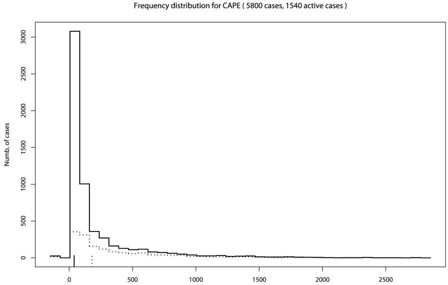

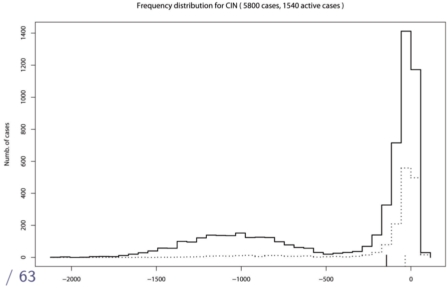

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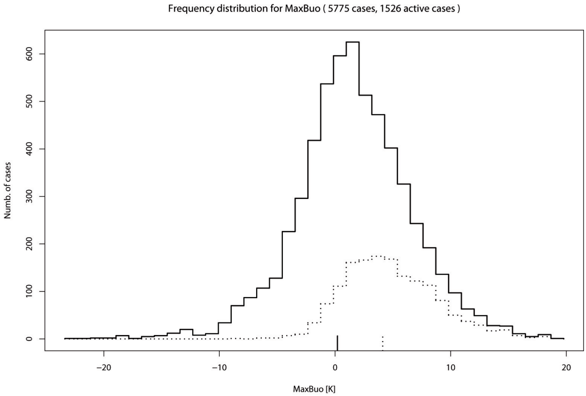
Also values of CIN$> -100J/kg$ are associated with convective events in the FVG plain.

Maximum Buoyancy and Downdraft Potential



Storms are more likely when MaxBuo> -2K. Morgan and Tuttle (1984) defined MaxBuo but also other indices, like the difference between the maximum Θ_{es} in the low levels and the minimum Θ_e in the mid levels, called *Downdraft Potential*. DownPot$=$ $Max(\Theta_{es}|_{low}) - Min(\Theta_e|_{mid})$.

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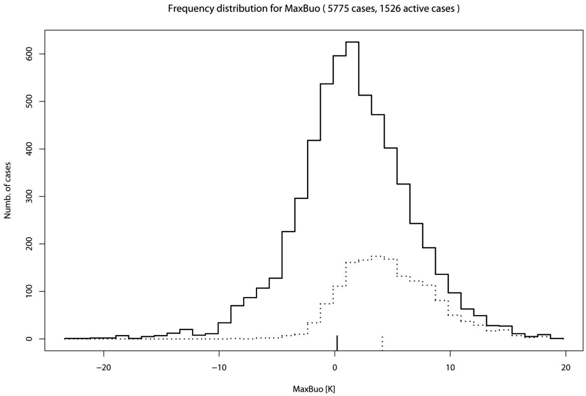

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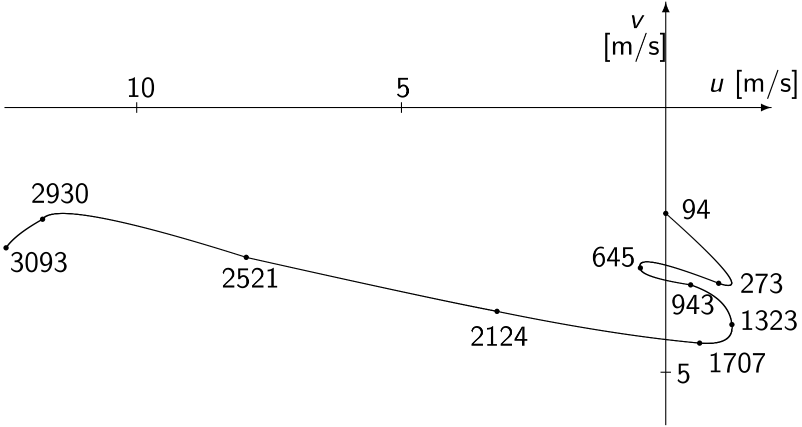
Physical meaning: the coolest and more dry air in the middle troposphere [$Min(\Theta_e|_{mid})$] is supposed to saturate by rainfall evaporation and hence is brought down along a saturated pseudo-adiabat (Θ_e is conserved). The maximum thermal contrast (generating the outflow wind) will happen at the low level where Θ_{es} is maxima. It measures the *negative buoyancy*.

Wind hodograph and shear



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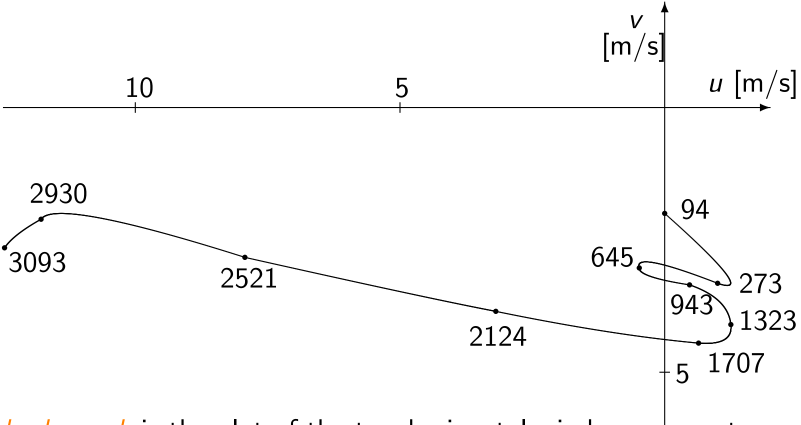

The *hodograph* is the plot of the two horizontal wind components u and v. The hodograph path length is called Shear.

$$\text{Shear} = \frac{\int_{z_0}^{z_N} \left\| \frac{\partial \vec{W}}{\partial z} \right\| \cdot \mathrm{d}z}{z_N - z_0} \cong \frac{\sum_1^N \sqrt{(u_n - u_{n-1})^2 + (v_n - v_{n-1})^2}}{z_N - z_0} \quad (18)$$

Bulk shear

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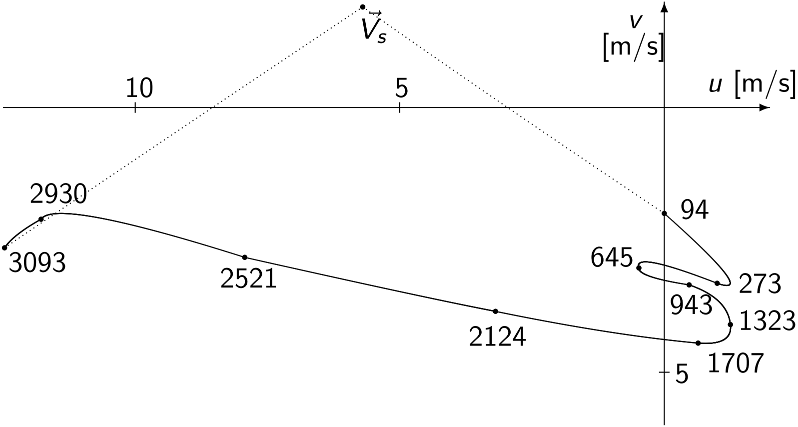
- For example, the Bulk Richardson Number is defined as 2 times CAPE divided by the square of the bulk shear between 6 km and 500 m: BRN$= 2\frac{\mathrm{CAPE}}{{S_{BRI}}^2}$.
- In very complex orography terrains, like northern Italy, it is not obvious that shear will have the same importance in governing storm organization (single cell, multicell, squall lines) as it has been found in the US's plains, because of the complex interaction between winds and orography...

Storm–Relative Helicity



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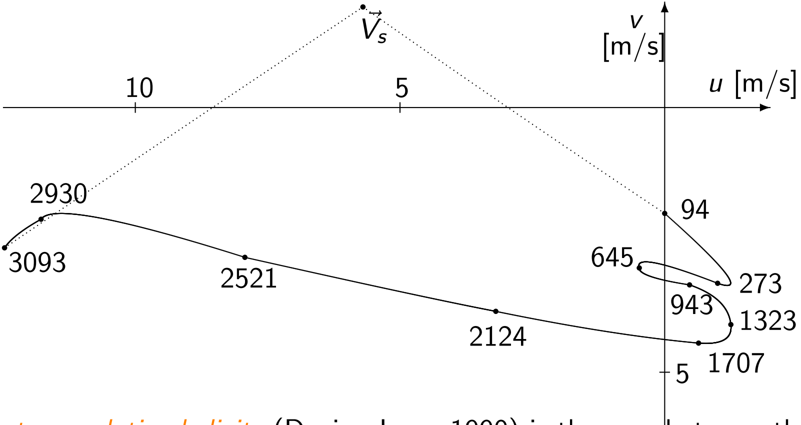
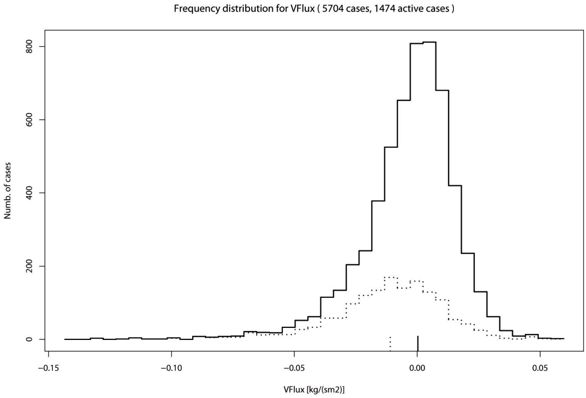


The *storm-relative helicity* (Davies-Jones 1990) is the area between the storm-velocity vector, V_s, and the hodograph. Usually integrated up to 3 km.

$$\mathrm{SRH} = -\int_{z_0}^{z_N} \vec{k} \cdot (\vec{W} - \vec{V_s}) \times \frac{\partial \vec{W}}{\partial z} \cdot \mathrm{d}z \cong -\sum_{1}^{N} (u_n - u_s)(v_n - v_{n-1}) - (u_n - u_{n-1})(v_n - v_s) \qquad (19)$$

Should be useful for supercells and tornadoes.

Water Vapor Flux in the lowest 3 km



In FVG (Adriatic Sea on the South and Alps on the North) we have found to be very useful the *water vapor flux* in the lowest 3 km:

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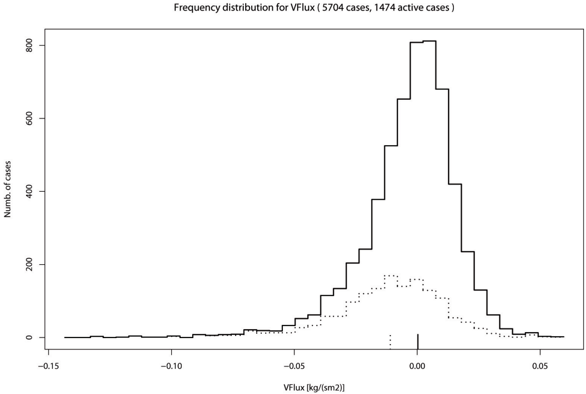

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Physical meaning: strong moist winds blowing from South (VFlux< 0) brings the "convective fuel" against the orographic barrier, producing convection triggered by orographic lifting or strong precipitating systems (especially in autumn). Useful in particular for heavy rainfall forecast.

Example of SOUND_ANALYS.PY output in a HTML page

SOUND_ANALYSIS RESULTS:

Year	Month	Day	Hour
1998	06	28	12

Udine Sounding (WMO code 16044,
managed by the Italian Aeronautica Militare)

Index [5 : 95 percentils unit on all cases April-November 1995-2007]	T	Tv	Tvc
MUP ThetaE [296:336 K] **Thetae**	337.2	337.2	337.2
MUP Mixing Ratio [2.2:12.5 g/kg] **Mix**	12.4	12.4	12.4
MUP height [228:2434 m] **h_MUP**	271	271	271
Convective Available Potential Energy [0:923 J/kg] **CAPE**	1124.2	1243.1	1220.4
Convective Inhibition [-1385:-0.4 J/kg] **CIN**	-46.4	-14.7	-25.0
Tropopause height [9298:13611 m] **Trop**	12514	12514	12514
Cloud top [2279:11687 m] **EL**	11506	11464	11857
Lev. of Free Convection [925:4136 m] **LFC**	2932	2080	2608
Cloud base height [648:3553 m] **LCL**	1469	1469	1469
Cloud base temperature [-12.2:15.3 C] **Tbase**	14.5	14.4	14.4
Boundary Layer Top [313:4297m] **PBL**	752	752	752
Melting level [1720:4338 m] **MEL**	4402	4587	4312
Wet Bulb Zero [921:3590 m] **WBZ**	3421	3421	3421
Max Updraft velocity [0:29.3 m/s] **UpDr**	29.7	32.6	26.0
Max Hail diameter [0:4.8 cm] **HD**	5.0	6.0	3.8
Precip. Wat. Env. [9.1:36.4 mm] **PWE**	34.5	34.2	34.2
Precip. Wat. Cloud [0:44.5 mm] **PWC**	44.3	44.1	44.4
sfc-250hPa Low Rel. Humidity [38:91 %] **LRH**	64.1	64.1	64.1
sfc-500hPa Medium Rel. Humidity [31:88 %] **MRH**	58.7	58.7	58.7
500-300hPa High Rel. Humidity [11:71 %] **HRH**	22.5	22.5	22.5
CAP diff. theta_es [1.3:17.8 C] **CAP**	1.4	1.4	1.4
Low buo. accel. [-44:31cm/s2] **b_PBL**	-47.0	-47.0	-47.0
Downdraft Potential [3.5:52.4 K] **DownPot**	47.6	47.6	47.6
Maximum Buoyancy [-9.8:9.6 K] **MaxBuo**	10.33	10.33	10.33
Lifted Index 500m [-2.57:13.0 C] **LI**	-3.22	-3.74	-2.01
Diff. Temp. 500hPa [-3.3:9.4 C] **DT500**	-3.3	-3.81	-2.11
Diff. Temp. at -15 [-3.5:7.0 C] **DTC**	-2.89	-3.27	-2.76
Showalter Index [-1.0:11.7 C] **ShowI**	0.06	-0.28	0.8
Stabil. Wind Shear Index Switz.) [-4.3:15.9] **SWISS**	-3.2	-3.7	-2.0
Severe WEAth. Threat [7.4:186] **SWEAT**	129.5	129.5	129.5
K Index [-4.9:33.4 C] **KI**	28.7	28.7	28.7
Boyden Index [91.6:98.9] **BOY**	95.4	95.4	95.4
Vapour Flux [-41:20 gm-2s-1] **VFlux**	-31.7	-31.7	-31.7
U Low Lev. Wind [-2.7:7.6 m/s] **LLWu**	0.5	0.5	0.5
V Low Lev. Wind [-4.0:3.9 m/s] **LLWv**	-3.1	-3.1	-3.1
U Med. Lev. Wind [-10.3:5.7 m/s] **MLWu**	-7.6	-7.6	-7.6
V Med. Lev. Wind [-13.2:4.3 m/s] **MLWv**	-3.1	-3.1	-3.1
U High Lev. Wind [-31.3:9.9 m/s] **HLWu**	-23.9	-23.9	-23.9
V High Lev. Wind [-18.6:24.4 m/s] **HLWv**	-4.2	-4.2	-4.2
Low Level Jet (>15m/s) Depth [0:2776 m] **LLJD**	387	387	387
High Level Jet (>30m/s) Depth [0:4781 m] **HLJD**	0	0	0
Bulk Richardson Numb. [0:86] **BRI**	34.1	37.5	36.8
Bulk Shear sfc-850hPa [1.2:11.5 m/s] **BS850**	1.7	1.7	1.7
Shear * E-3 [4.0:14 s-1] **Shear**	4.6	4.6	4.6
Shear * E-3 [5.0:17 s-1] **Shear3**	0.0	0.0	0.0
Helicity [-55:127 J/kg] **Hel**	50.1	50.1	50.1
Storm Rel. Helicity [-18:187 J/kg] **Rel_Hel**	65.2	65.3	65.3
Energy-Hel. [-0.004:0.298 m4/s4] **EHI**	0.46	0.51	0.5
Radiosonde vertical vel. [3.78:5.53 m/s] **VV**	4.46	4.46	4.46
Stand. dev. vertical vel. [0.25:0.97 m/s] **VVstd**	0.39	0.39	0.39

Sounding Analysis results

Kelvin = Celsius + 273.15

See Thetaplot example for some variable definitions

See Sound_Analys.PY Handbook for more details

Developed by agostino.manzato@osmer.fvg.it

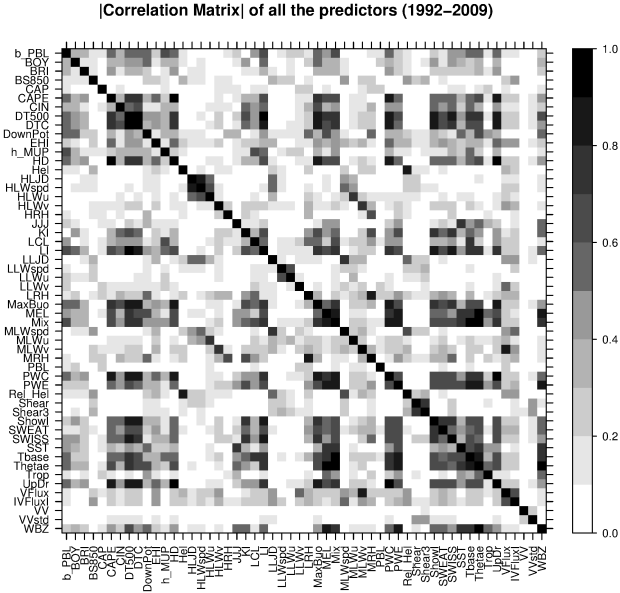
Another sounding

HOME

Just an example of the many indices computed by SOUND_ANALYS.PY for the Udine 1998/06/28 12 UTC sounding.
The three methods "T", "T_v" and T_{vc} are explained in Manzato and Morgan (2003).

Matrix of inter-correlations among sounding-derived indices

Manzato JAMC 2012 has studied the correlations among 52 indices derived from 1992–2009 00, 06, 12 and 18 UTC Udine soundings.
These indices can be seen as a non-linear reduction of 3D basic atmosphere variables (p, T, RH, Θ_e, wind at many levels) into a set of intercorrelated parameters.



3 groups of indices highly inter-correlated (R$\geq$ 0.80)

1. Indices related to the most unstable parcel, like its equivalent potential temperature (Θ_e), its mixing ratio (Mix) and the height where its ascent temperature becomes 0 °C (MEL), or related to other environmental characteristics, like the height where the atmospheric wet bulb temperature becomes 0 °C (WBZ) and the precipitable water integrated along the entire atmospheric column (PWE).

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2. Indices of "two–levels" potential instability such as Lifted Index (Galway 1956), Showalter Index (Showalter 1953), DT500 and DTC (Manzato 2003), i. e. the "lifted index family". Also the Maximum Buoyancy (Morgan and Tuttle 1984, Manzato and Morgan 2003,) is very well related to three of these indices.

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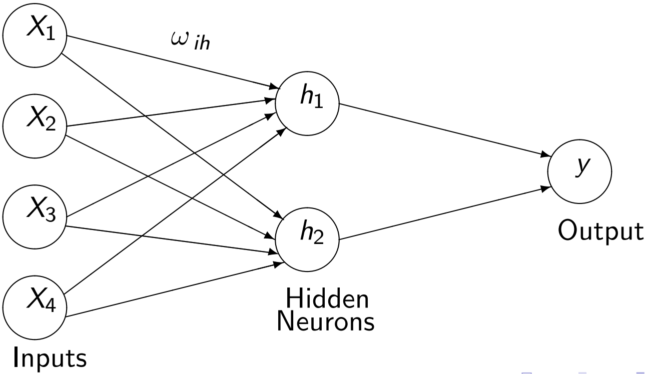
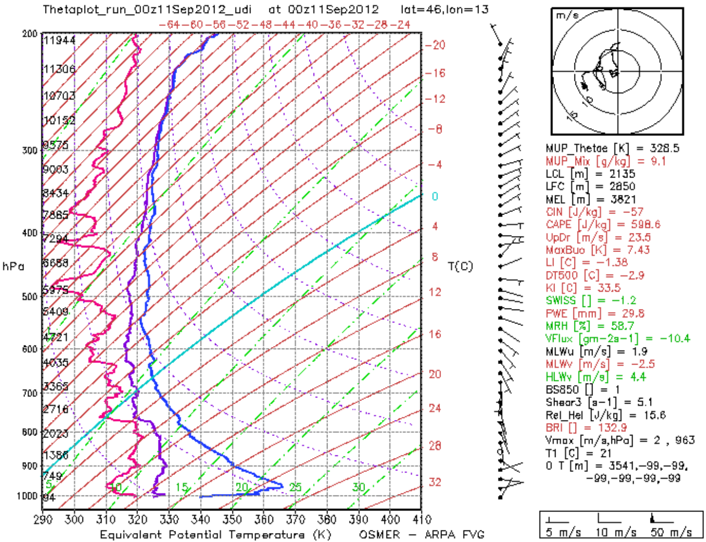
3. Indices of "integrated" potential instability, i. e. maximum updraft velocity (UpDr), hail diameter (HD), CAPE and precipitable water integrated between LFC and the equilibrium level (PWC). MaxBuo is also well correlated with three of these indices.

Section 5

Forecasting meteo events with sounding-derived indices



The simplest way to use indices is setting a threshold



Here you can see a Thetaplot + hodograph + index table made by Arturo Pucillo (OSMER) in GrADS.

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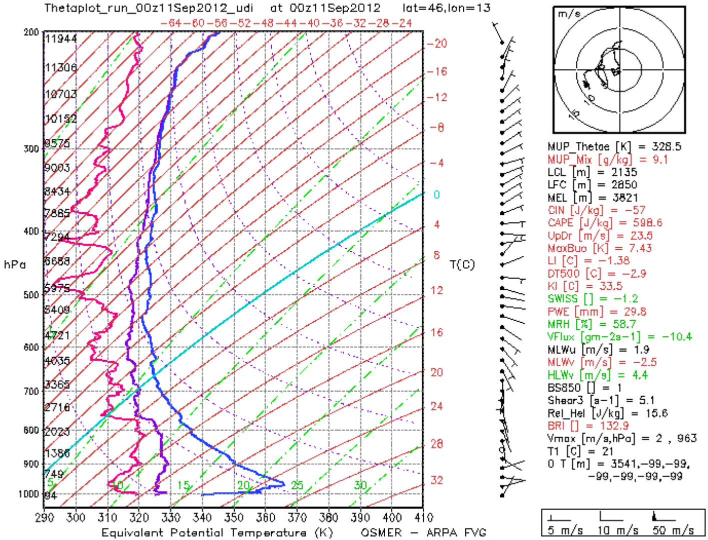

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Note the red–green colors when a statistical threshold (found maximizing the Pierce Skill Score) is exceeded.

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- When a complex statistical method is applied, like one with many predictors or non–linear models (neural networks), it is mandatory to avoid the *overfitting*. A good way is to develop the model fitting a *trainig* set and choosing the model that optimize the *validation* set. Lastly, an independent *test* sample should be used.

Pre-processing the input data

- For any forecasting problem it should be clarified if it is a classification problem (forecasting among a few class categories, e.g. binary events) or a regression problem (forecasting the value of a continuous variable), because the statistical models applied are different and also the forecast verification techniques are different (e.g. contingency table vs. Taylor diagram).

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- For example, for regression problems, it is a commonly to standardize each variable, subtracting the mean value and dividing for the standard deviation.
- For the classification problem, we suggest to transform each variable in its empirical posterior probability of event occurrence, as explained in Manzato (2005).

Section 6

Conclusions

"Pazzo è bene da catene,
Chi fastidio mai si dà
Per saper quel che sarà..."

He is a raving madman
who ever takes the trouble
to know what the future holds...

from the first act of "Sant'Alessio" (1631) by Stefano Landi (1587–1639), text by Giulio Rospigliosi (1600–1669, also known as Pope Clemente IX).

Conclusions

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- Try always a multivariate approach because more indices are better then a few and be careful to avoid overfitting in your verification process.

Thanks! For info: *agostino.manzato@meteo.fvg.it*

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