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On an energetic index for local instability

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RESUMEN

En un trabajo anterior se indroduce un índice energético de inestabilidad local (IR), definido como la diferencia entre la energía estática húmeda (h) en el nivel de 850 hPa y la energía estática saturada (h*) en el de 500 hPa.

En este artículo se calcula IR a partir de 245 sondeos sobre España (Madrid-Barajas) y otras localidades europeas (Roma, Berna, Viena, Burdeos y París). A partir de estos datos se demuestra la aplicabilidad operativa del índice. Asimismo se relacionan los valores del índice con la estabilidad de la columna atmosférica (teniendo en cuenta diversos tipos de inestabilidad) y con la probabilidad de desarrollo de hidrometeoros de origen convectivo. Además se efectúa una comparación entre los resultados ofrecidos por los índices IR, Showalter y Total de Totales.

ABSTRACT

In a previous work an energetic index for local instability (IR) was introduced. This index is defined as the difference between moist static energy (h) at 850 hPa pressure level and saturated static energy (h*) at 500 hPa pressure level.

In this paper IR is evaluated from 245 soundings over Spain (Madrid–Barajas) and other European points (Rome, Berne, Vienne, Bordeaux and Paris). From this evaluation the operative applicability of this index is shown. In the same way index values are related to instability (taking into account several types of instability) and probability of convective hydrometeors. Furthermore a comparison between IR, Showalter, and Total Totals indexes is made.

1. Introduction

Convective development is a mechanism which tends to eliminate the vertical energetic unbalances generated in the atmospheric column. In consequence, an appropriate description of the convection in energetic terms may be established. As it will be seen in section 2, appropriate energetic magnitudes are moist and saturated static energies. These energetic magnitudes are usually used in cumulus parameterization models (i.e., Yanai *et al.*, 1973; Arakawa and Schubert, 1974). García Díez *et al.* (1987) carried out an operative energetic method for analysis and prediction of convective phenomena using vertical profiles of dry, moist and saturated static energy. Rivas Soriano and García Díez (1991b) deduced that convective instability phenomenon appears as a first order discontinuity in $h(p)$ (moist static energy); consequently, in vertical profile of energy versus pressure the atmospheric column can be considered as a barrier-well succession in the energy. This model allows to define an energetic index of local instability, so-called IR, as the difference between barrier height and well depth.

Previously, Darkow (1968) defined other energetic index for instability but, in contrast to IR, it does not take into account the relationship between instability and energy needed for its release, nor the water vapour condensation influence. Consequently Darkow index is valid only for situations of great instability, as tropical cyclones, while IR index has a more general validity.

An instability index is useful to get a relationship between index values and convection probability. Consequently, in this paper such a question is going to be undertaken.

2. Static energies and convective instability

The total energy per unit mass can be written as

$$E = V^2/2 + C_p^\prime T + gz + Lq + L_1 q_1 \tag{1}$$

where V, $C_p^\prime$, T, g, z, q, L, q_1, L_1 are the velocity, specific heat of real air, absolute temperature, gravity, geopotential height, specific humidity latent heat of condensation, liquid water content and latent heat of freezing, respectively. Sinse a) the kinetic term is about two orders of magnitude lower than remainder, b) in the atmosphere water vapour and liquid water entalphies are negligible with respect to dry air entalphy and c) supercooled state is usual in the atmosphere, then eq. (1) can be approximated to

$$h = C_p T + gz + Lq \tag{2}$$

In which h is the moist static energy and C_p the specific heat of dry air. In extreme cases it is obtained:

$$h = C_p T + gz = M \tag{3}$$

$$h = C_p T + gz + Lq^* = h^* \tag{4}$$

where M is the Montgomery potential or dry static energy, $q^*(z,\ T)$ the saturated specific humidity and h^* the saturated static energy.

Convective instability can be described in terms of these energetic magnitudes. In effect, M, h and h^* verify (Fraedrich 1973; Arakawa and Schubert 1974; Rivas Soriano and García Díez 1991a, b).

$$dM = C_p T d\theta/\theta$$

$$dh = C_p T_e d\theta_e/\theta_e \tag{5}$$

$$\partial h^*/\partial z = A(\Gamma - \alpha)$$

in which θ is the potential temperature, T_e the equivalent temperature, θ_e the equivalent potential temperature, Γ the adiabatic lapse rate of saturated air, α the vertical lapse rate and A a positive function of T and q^*. Consequently an atmospheric column is unstable when

$$\partial M/\partial z < 0 \text{ (dry air)} \tag{6}$$

$$\partial h/\partial z < 0,\ \partial h^*/\partial z < 0 \text{ (moist and saturated air)} \tag{7}$$

In Figure 1, vertical profiles of M, h and h^* in a convective unstable column are shown. If it is required that air particles are in energetic equilibrium with the environment in their forced ascent to the convective condensation level (CCL), then such ascent can be represented by a straight line parallel to $M(p)$ going through $h(p_o)$ being p_o the pressure level at which the particles for convection to start.

When the CCL is reached, air particles ascent by themselves and, as first approximation, without exchange of energy with environment (path 2 in Fig. 1). Area A_2 represents the available energy for convective phenomena or instability energy.

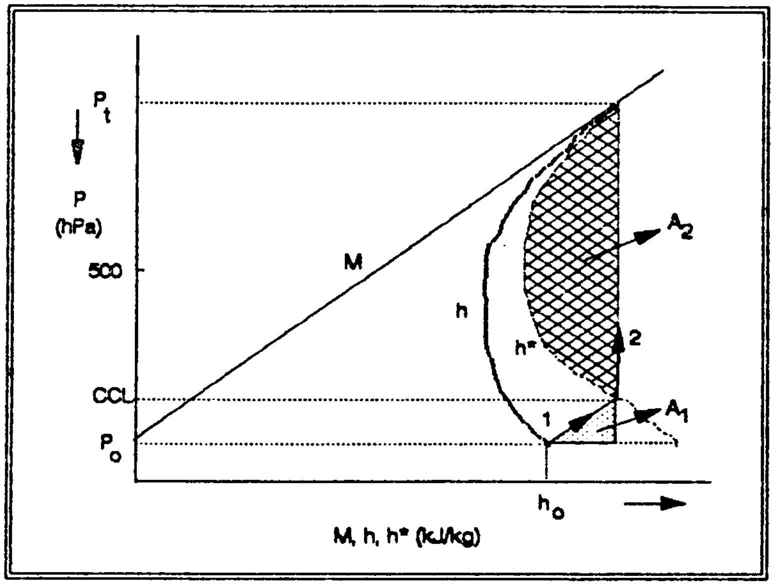

Fig. 1. Vertical profiles of dry, moist and saturated static energies in a situation of convective instability.

Consequently, a simple energetic criterium of convective instability may be established in comparative terms of A_1 versus A_2:

a) Stability: area A_2 is very small or does not exist.

b) Negative latent instability: Areas A_1 and A_2 are comparables, but the first one is bigger.

c) Positive lantent instability: A_2 is big and A_1 is small

d) Strong positive latent instability: c case is very stressed to instability.

3. The IR index

The above mentioned method is based on a comparison between areas. Two previous considerations are required:

i) to know M, h and h^* in a sufficient number of pressure levels in order to deduce $M(p)$, $h(p)$ and $h^*(p)$ curves

ii) to evaluate A_1 and A_2 areas.

Consequently, from an operative point of view, it is interesting to have an index that contains the same information that the difference $A_2 - A_1$. Analyzing Figure 1, this index can be established as follows (Rivas Soriano and García Díez 1991b). If it is assumed that $p_o = 850$ hPa, the area A_1 will become larger the more $h(850)$ approaches to the left with respect to $h^*(CCL)$. In consequence A_1 can be estimated by $h^*(CCL) - h(850)$. On the other hand, since the inflection point of $h^*(p)$ curve is generally located between 600 and 400 hPa, A_2 will become larger the more $h^*(500)$ is to the left with respect to $h^*(CCL)$. For this reason, A_2 can be estimated by $h^*(CCL) - h^*(500)$. Thus strong convective instability will be associated with high values of the IR index defined as:

$$IR = (h^*(CCL) - h^*(500)) - (h^*(CCL) - h(850)) =$$

$$= h(850) - h^*(500) \tag{8}$$

The physical meaning of this index is clear. The environment $h(850)$ value is a measurement of energy required to start instability. In effect, if an air particle at low levels is taken from the environment, the more energy it has, the less energy will be needed to supply to begin instability. Consequently, high $h(850)$ values inply low supply of energy.

Similarly, the environment $h^*(500)$ value is a measurement of the instability energy. In effect, if it is assumed that convective ascent is roughly adiabatic, and that at 500 hPa air particles are saturated, the less $h^*(500)$ is, the more energy excess with respect to the environmental air particles will have and, consequently, the ascent will reach higher levels.

It must be pinpointed that the compute h at 850 hPa is more realistic in continental zones. In coastal zones a better approximation could be to compute h at 900 or 1000 hPa since water vapour content between surface and 850 hPa level can play a significant role in convective development.

4. Results and discussion

As working data set we have considered several episodes which were considered as "notable convective phenomena" by the Bulletin W. M. O. (1976, 1977, 1979, 1982, 1983). Also, some cases registered over Spain were analyzed. On the other hand, in order to establish a more general validity of this index, a temporal sequence of daily soundings over Madrid is included. Analyzed soundings are at 0000 UTC and for years between 1956 and 1983.

Since a first question was to analyze a possible relationship between IR values and instability type. In Table I are presented IR values versus instability type, classified as in section 2. A second problem includes the comparison between IR values and subsequent hydrometeors registered (Table II).

Analyzing results of tables I and II, Table III can be established, in which IR values and subsequent weather are related. It may be seen the quality of IR values as predictor index.

In this sense IR index has been compared with Showalter and Total Totals indexes, perhaps the two indexes of most windespread operative use. This comparison was established on the basis of the analysis of 31 soundings along July 1987 over Madrid-Barajas at 0000 UTC. Results are in table IV.

In all cases, IR values have been computed in kJ/kg and percentages in tables I and II are deduced of the number of times that each situation appears with the indicated IR value.

Table I shows how the IR index describes the convective instability of atmospheric column, that is, if IR is a good approximation to the $A_2 - A_1$ value. It is seen that when IR is positive, in 100% of cases positive latent instability exist and in 79% is strong. On the contrary, when IR is less than -4 there are not cases with strong instability and when IR is less than -9 only 6% of cases present positive latent instability. Those cases where IR ≤ -9, and positive latent instability, correspond to exceptional situations where the inflection point of the $h^*(p)$ curve is situated far below with respect to 500 hPa pressure level. In this case (Fig. 2) $h^*(CCL) - h^*(500)$, and consequently IR, does not propertly estimate the instability energy A_2.

Table I. IR/stability relationship

	IR>0	-3≤IR≤0	-8≤IR≤-4	IR≤-9
Strong positive latent instability	79 %	7 %	0 %	0 %
Positive latent instability	21 %	80 %	34 %	6 %
Negative latent instability	0 %	12 %	39 %	20 %
Stability	0 %	1 %	27 %	74 %

Table II. IR/convective hydrometeors relationship

	IR≥0	-4≤IR≤-1	-9≤IR≤-5	IR≤-10
Storms or Showers	85 %	75 %	43 %	12 %
Very Cloudy	7 %	13 %	20 %	4 %
Less cloudy or sky clear	8 %	12 %	37 %	84 %

Table II shows the relationship between IR and convective hydrometeors. It is seen that positive IR (strong instability after Table I) it is corresponded in most of the cases (88%) with convective precipitation, and the decreasing of IR value is correlated with a decrease of hydrometeors of convective cause, in such a way that when IR ≤ -10 (stability after Table I) in the most of cases (84%) there is not cloudiness.

Table III.

index value	instability	convective hydrometeors
IR≥0	Strong positive latent instability	generalized showers and storms
-1≥IR≥-4	Positive latent instability	very cloudy with high probability of showers and storms
-5≥IR≥-9	Negative latent instability	cloudy or less cloudy
IR≤-10	Stability	less cloudy or sky clear

Table IV. Comparison between Showalter (SI), Total Totals (TI) and IR indexes

Day	SI	TI	IR	Reported weather
1	-2.0	47	-3	Showers and Storms
2	-0,5	48	-2	Showers ans Storms
3	-1.0	46	-4	Showers and Storms
4	-1,0	49	-2	Showers and Storms
5	-1.0	45	-5	Showers and Storms
6	-1.5	50	-1	Showers and Storms
7	3.0	45	-6	Showers and Storms
8	3.0	43	-7	Showers and Storms
9	-1.0	50	0	Showers and Storms
10	-0.5	48	-1	Showers and Storms
11	0.0	49	-1	Showers and Storms
12	1.0	47	-3	Showers and Storms
13	1.0	47	-3	Showers and Storms
14	5.0	42	-8	Showers
15	4.0	41	-9	Sky clear
16	3.0	44	-6	Sky clear
17	4.0	39	-10	Sky clear
18	4.0	40	-9	Sky clear
19	8.0	39	-16	Sky clear
20	10.0	32	-17	Sky clear
21	6.5	37	-12	Sky clear
22	5.0	41	-9	Sky clear
23	1.0	46	-5	Sky clear
24	2.0	46	-4	Sky clear
25	-1.5	52	1	Showers and Storms
26	4.0	42	-9	Sky clear
27	9.0	37	-21	Sky clear
28	4.5	42	-9	Sky clear
29	-3.0	53	2	Showers and Storms
30	3.0	45	-6	Sky clear
31	8.0	36	-7	Sky clear

These results are consequence of the good adjustment between IR index and convective instability deduced from Table I. Because convective instability does not necessarily imply convective hydrometeors, Table II must have more exceptions than Table I. In effect, the generation of hydrometeors requires, as a previous condition, the supply of energy A_1 necessary for convection to begin and if this supply does not exist then hydrometeors will not appear. For this reason there are some cases with less cloudiness or clear sky with IR> -4 in Table II. Since the smaller the area A_1 is, the more easily convection begins, thus 12% of the cases with less or none cloudiness for $-4 \leq$IR≤ -1 are reduced to 8% for IR≥ 0.

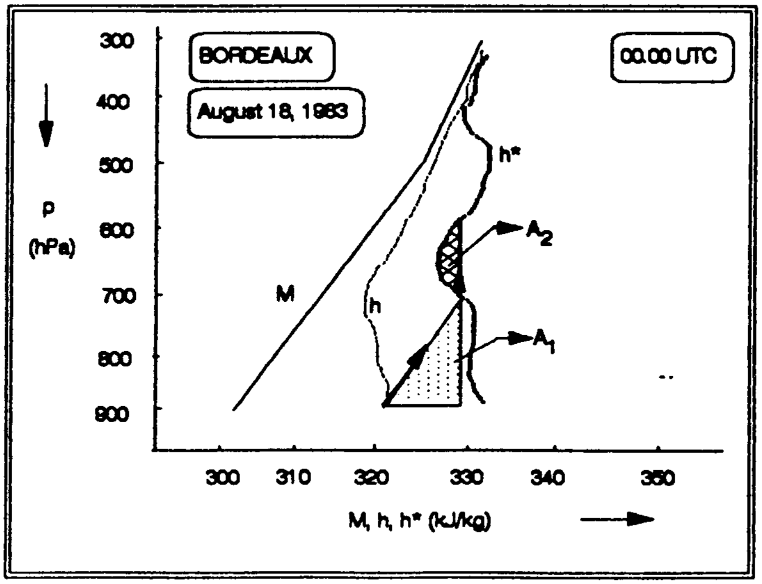

Fig. 2. As in Fig. 1 at 0000 UTC 18 August 1983 over Bordeaux

Similarly less or none instability does not necessarily imply absence of convective clouds because in the atmosphere there are other types of instability. For example, the moist slantwise instability that can cause convective phenomena even in a stable atmosphere for moist adiabatic vertical displacements (Thorpe and Emanuel, 1985). This explains some cases of convective precipitation with little instability or even stability (12% with IR≤ -10 in Table II).

For an operative use of the Table III, it must be taken into account that inside each category of IR values the more IR is, the more instability and probability of convective hydrometeors will have.

Table IV shows that IR index has a similar performance to Showalter index and slightly better than Total Totals index. In effect, if the values Showalter $= 3$, Total Totals $= 48$ and IR $=$ -5 are taken as threshold values for the generation of convective hydrometeors, it is seen that Showalter and IR indexes present 5 failures and Total Totals index 8 failures.

5. Conclusions

In this paper the validity of an energetic index for diagnosis of convective instability has been analyzed. It has been shown that IR index has an analogous performance with respect to Showalter and Total Totals indexes. On the other hand, since IR is an energetic balance, which includes the most significant energies in a convective process, it has more theoretical significance than other indexes and, consequently, it has a general validity, whichever is the process causing convective instability (soil heating, moist advection at low levels or high level cooling).

On the other hand, this energetic index presents supplementary advantages: it allows to connect with cumulus parameterization models and to build easily instability maps at synoptic or mesoscalic scales.

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