When forecasters were ahead of the theoreticians - the case of "downstream development"

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"Of course, what is really needed is a good synoptic meteorology book that would address [downstream development] instead of describing 49 different kinds of occlusions"
(Letter from J. R. Holton to A. Persson, 13 March 1995).

Although now retired, I have for many years been the lucky recipient of this journal. I have seen many interesting articles dealing with operational forecasting, severe storms and flooding etc, but none about what is called "downstream development". During my time at ECMWF, lecturing on training courses, this topic was perhaps one of the most popular.

"Downstream development" refers to the common occurrences of successive baroclinic developments, propagating eastward with a speed of 25-30°/day, like some sort of "domino effect". I learned about it from the forecasters at the Swedish Meteorological and Hydrological Institute (SMHI) when I started there in 1968. It fascinated me immediately. It made me realise how tomorrow's weather over Sweden was not only dependent on the arriving cyclone over the North Sea, but perhaps also of another cyclone, further upstream in the North Atlantic.

When I joined the Met Ops Section at ECMWF in 1991 the mechanism of "downstream development" proved useful for tracing the origin of bad forecasts. The greatest trophy was when we once managed to trace a bad 7-day forecast to an erroneous radiosonde observation on the Kamchatka peninsula.

It started more than 80 years ago.

It was in the 1930's, when the data coverage over the oceans improved, that weather forecasters started to notice that individual high and low pressure systems seemed to interact with each other. In 1936 the Norwegian meteorologist **Sigurd Evjen** (1894-1956) published a paper in the then

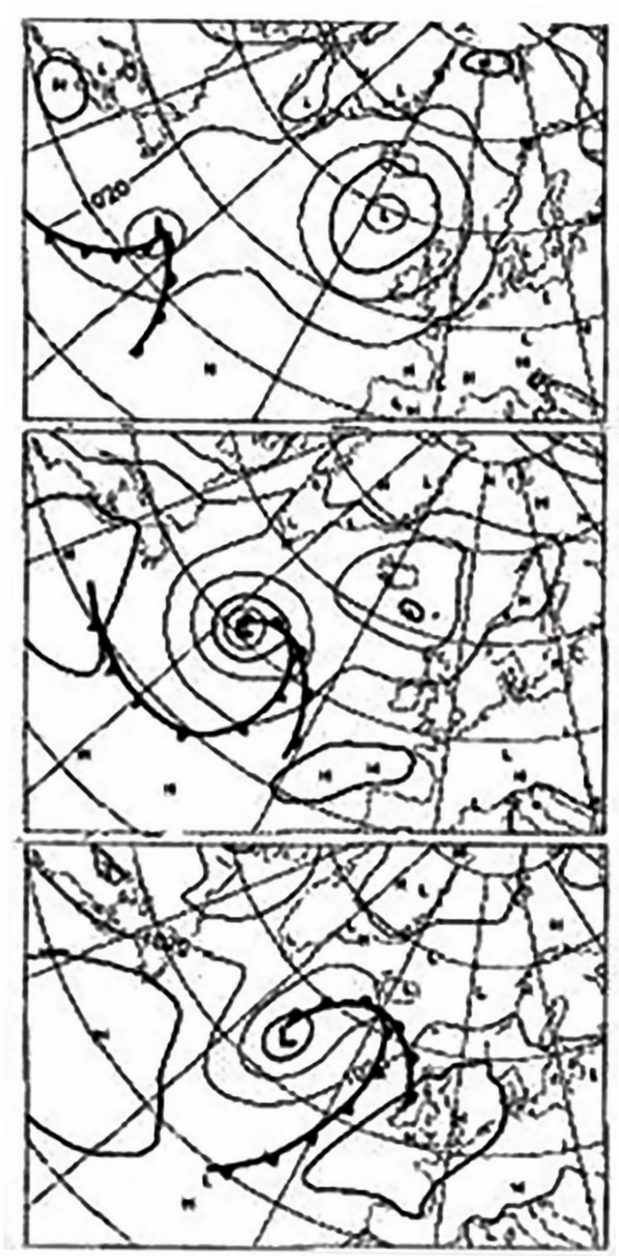

Figure 1: "Cyclone murder"? A reconstruction of what Sigurd Evjen saw in the 1930's, taken from ECMWF analyses (or forecasts) from the late 1990's (exact date unknown).

leading journal, *Meteorologische Zeitschift*, about what he had seen:

"*I have after many years of work in practical forecasting found that when a cyclone intensifies over the North Atlantic, a strong and persistent rise is to be expected further to the east. This pressure rise cannot only exterminate an old area of falling pressure, but also fill an old cyclone (*"*Cyclone murder*"*)... For example a strong cyclogenesis just east of Newfoundland may already the next day affect the weather in Norway. The easterly pressure rise can in its turn lead to a second cyclone deepening and cause rapid changes in the whole pattern further to the east... I have so far not found any case where a strong and persistent pressure rise has occurred west of an intensifying cyclone (Evjen, 1936, 168, 172).*

He tried to explain it as a result of huge quantities of air being released from the deepening cyclone and then transported downstream by the upper-air flow. He was on the right track, although what was transported by the upper tropospheric flow was, as it turned out, not *mass* but *energy*.

From the Gulf of Alaska...

During the Second World War, when the network of aerological stations was built up over North America, two meteorologists at the University of Chicago, **Jerome Namias** and **Philip Clapp**, noticed a similar synoptic behaviour in upper air patterns over North America. In January 1945, at the 25th anniversary meeting of the founding of the American Meteorological Society in Kansas City, Namias made a public disclosure of their discoveries under the heading "*Some Interrelations of Weather Phenomena Over the Northern Hemisphere*":

"*In order to obtain perspective in making forecasts for periods longer than 24 hours, meteorologists must expand their horizon in both space and time. The expansion in space is necessary because weather phenomena occurring at far distant points may exert an amazingly fast influence in the territory of the forecaster... In one case in September 1944, the rapid development of an upper level trough in the Gulf of Alaska affected the weather downstream as far as western Europe in four days...*"

The September 1944 case was not an isolated one. An intensification of a storm in the Gulf of Alaska was frequently followed by a downstream strengthening of a high pressure system over the western USA and, in a few days, followed by a new low-pressure system developing downstream over eastern USA. This "downstream development" process could continue further downstream and profoundly affect the circulation over extensive parts of the hemisphere (Namias and Clapp, 1944, p. 65).

"Group velocity"

At about the same time the Swedish-American meteorologist and dynamicist, **Carl Gustaf Rossby**, on vacation in California, had, just by listening to the sound of the incoming Pacific Ocean waves, found a theoretical way to describe the "downstream development» process as a matter of "group velocity"[1].

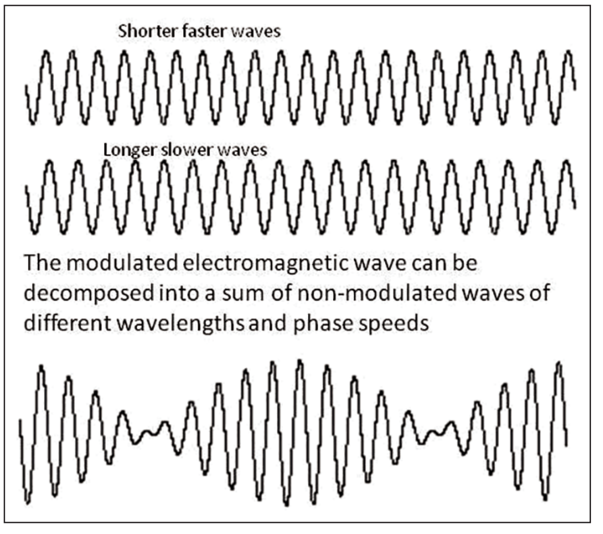

Figure 2: Group velocity as the interference pattern of two monochromatic wave systems moving with slightly different velocities. The concept was discovered in the late 1800s and used to understand sound and electromagnetic waves.

The concept of "group velocity" can most easily by illustrated by two combs with slightly different spacing between the "teeth". When they are put together and moved, the inference pattern moves with its own velocity, the "group velocity". At a more advanced level "group velocity" can be illustrated by the interference of sine waves of different wave lengths moving with different phase speeds.

"Group velocity" can be seen as the speed of wave activity or "energy". Rossby, who was also

1. It would take too long to tell the wonderful story of Rossby's discovery. The interested reader is referred to my recent paper (Persson, 2017).

an oceanographer, knew that the energy in ocean waves travels half the speed of the waves themselves (phase speed). He was now curious to find out if the same applied to atmospheric waves. From his famous equation for phase velocities of planetary waves (c)

$$c = U - \frac{\beta L^2}{4\pi^2} \qquad (1a)$$

where U is the mid-tropospheric wind velocity, L the wave length and β the meridional variation of the Coriolis parameter, Rossby, using a superimposed model of sine waves, mathematically derived the "group velocity"

$$c_g = U + \frac{\beta L^2}{4\pi^2} \qquad (1b)$$

From (1b) it followed that for waves in the atmosphere, in contrast to waves in the oceans, the energy moved faster and ahead of the waves themselves (Rossby, 1945).

But how did this "group velocity" manifest itself physically, synoptically in the atmosphere? Rossby was, as he wrote in his paper, reluctant to substitute physical understanding with mathematical formalism. To discuss in terms of superposition of sine waves would be a "*recourse to artificially induced interference patterns*".

With this attitude he was quite unique among theoreticians, both then and now. As far as I have seen, today 90% of the textbooks use interference between sine waves to explain "downstream development". It is mathematically okay but it leaves the reader, as Rossby in 1944-45, with no clue what is "going on" in the atmosphere. What was to prove his luck was that Rossby had been a weather forecaster 1919-28. He therefore had respect for the weather forecasters' experience and was prepared to listen to them.

What the forecasters saw

In 1947 Rossby had moved back to Sweden and his old work place, the Swedish Meteorological and Hydrological Institute (SMHI). And now his theoretical derivations from the US met and merged with Scandinavian synoptic experience.

At a seminar Rossby held at SMHI he told about how *energy released in vigorous storms is transported with the group velocity, faster than the speed of the storm itself*. This rang a bell with one forecaster in the audience, **Ernest Hovmöller**. He was a Danish meteorologists, who just had settled in Sweden. He didn't quite understand what "group velocity" was but Rossby's words reminded him what a senior Danish forecaster, **Leo Lysgaard**, had once told him:

-*When there was an intense cyclogenesis west of Ireland, it was very probable that a strong high is created 1-2 days later over Central Europe*.

This was of course what was widely known among forecasters and had been expressed in Evjen's 1936 paper.

"Trough-ridge diagram"

The coupling between Rossby's theory and forecasters' experience led to the creation of the famous "trough-ridge diagram" or "Hovmöller diagram". Here the large scale wave patterns could be mapped as a function of longitude and time. Not only did the phase speeds of the synoptic waves (at 500 hPa or at any other upper tropospheric level) come out clearly but also, and perhaps more importantly, incidents of "downstream development".

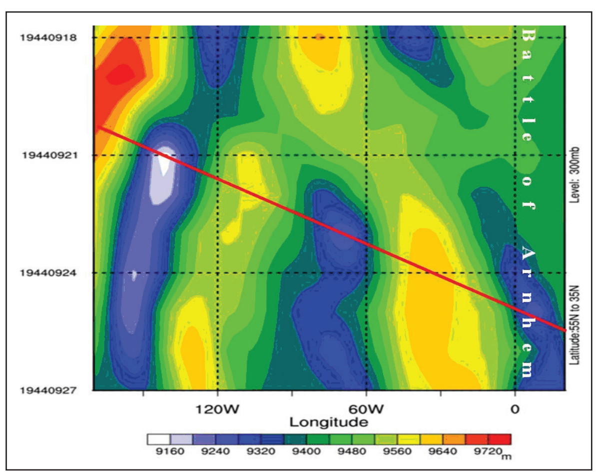

Figure 3: A Hovmöller diagram for 300 hPa geopotential covering North Pacific-North America-North Atlantic-western Europe 18-27 September 1944, the period Namias and Clapp had explored. The explosive development in the Gulf of Alaska at 140°W on 20 September triggered a downstream development which, with the speed of about 30°/day, reached Western Europe 25-26 September. At this time the Allied were involved in the "Battle of Arnhem". The arriving energy caused a cyclonic development over the Netherlands and worsened the weather which contributed to the Allied defeat.

Rossby was delighted. He could now see with his own eyes how the successive amplifications of waves downstream, a manifestation of the *energy* transport downstream, appeared in real life.

The "trough-ridge diagram" became an instant hit as well the concept of "downstream development". By the mid-1950's numerous papers on the subject had been published in meteorological journals, mainly American, German and Swedish (Tellus). About a third were theoretical and two thirds synoptic. "Group velocity" and "downstream development" were shown to be useful in real-time forecasting.

Parry and **Roe** (1952) investigated a case of a cold outbreak over the eastern USA, related to a chain of developments upstream, starting three days earlier, just east of Japan. **Carlin** (1952,1953) studied a "clear-cut" case where the influence could be traced over more than half the hemisphere. **Austin** *et al* (1953) found that for the winters through the period 1949-51, the concept of "downstream progression of change" verified well over North America and the neighbouring oceans. Then came a synoptic investigation by **Reed** and **Sanders** (1953) and many more. Forecasters made the interesting observation that the group velocity formula (eq.1b) was more suitable for synoptic application than the Rossby formula for phase velocity (eq. 1a).

Extension of the Bergen School model?

Rossby regarded the concept of group velocity as a definite break with the *local* character of the "Bergen School" cyclone model. However, with the exception of **Sverre Petterssen**, he never managed to convince either the Norwegian members of the "school" nor **Erik Palmén** about "downstream development" and "group velocity". In the late 50's the interest in these features waned among the theoreticians, more or less for the same reason as with the "Bergen school sceptics": they preferred to deal with unrealistic models of local conversion of energy rather than realistic models of propagation from another region. Nor had they any understanding or interest in operational forecasting.

One scientist who had became convinced, however, was **Tor Bergeron**. In a monumental book on weather forecasting he became almost lyrical in his description:

"*The energy in a train of waves is being propagated, not with their phase speed, which is less than the wind speed, but with the group velocity, which is greater. Attention is centred, in this new line of attack, not on the propagation of matter, for instance in the form of outbreaks of cold and warm air, but on the propagation of waves and atmospheric states, and thus energy, through matter.*" (Godske, *et al*, 1959).

The meteorologists who rose to management positions at SMHI in the 1950's were students of Bergeron or Rossby, or both. Hovmöller himself was still at SMHI, although he had left forecasting for climate research. When I joined the SMHI in the late 1960's his "trough-ridge diagram" was quite popular and "downstream development" or "group velocity thinking" was used in operational forecasting, in particular for forecasts beyond a day or two.

"Group velocity thinking" in daily use

It often happened that the forecasters, in particular at the five-day forecast section, started their overview of the synoptic situation far out in the North Pacific Ocean. In doing so, they followed the 1944 advice by Jerome Namias, who in 1949 had been a visiting scientist for half a year:

"*In order to obtain perspective in making forecasts for periods longer than 24 hours, meteorologists must expand their horizon in both space and time. The expansion in space is necessary because weather phenomena occurring at far distant points may exert an amazingly fast influence in the territory of the forecaster...*"

Being a more up to date forecaster than Bergeron and Rossby, Namias took part in the daily weather discussions and left a lasting impression on his Swedish colleagues.

Instances of "downstream developments", seen on the Hovmöller diagrams on the North Pacific, entering into the North American continent and the North Atlantic, were extrapolated into the European region and suggested possible changes of weather regimes. The resulting manual five day forecasts displayed predictive skill. From September 1965 SMHI confidently presented them publicly twice a week on the national television after the main evening news. *This was some years* *before reliable computer based numerical five day forecasts were produced at SMHI.*

Even when the operational NWP became more skilful "Hovmöller diagrams" remained in use. The NWP, which was able to produce "downstream development", could turn up new cyclones in "unexpected" places. Hovmöller's diagrams cautioned the forecasters to apply "group velocity thinking" and not to discard "odd" NWP solutions out of hand just because they did not adhere to the Bergen School synoptic rules.

A study by some students in 1977 found that the Swedish numerical forecast system (baroclinic up to +48h, then barotropic) slightly under forecast the group velocity, 20-25°/day instead of 25-30°/day in the 30-70º latitude band. This improved when the NWP was upgraded to higher resolution.

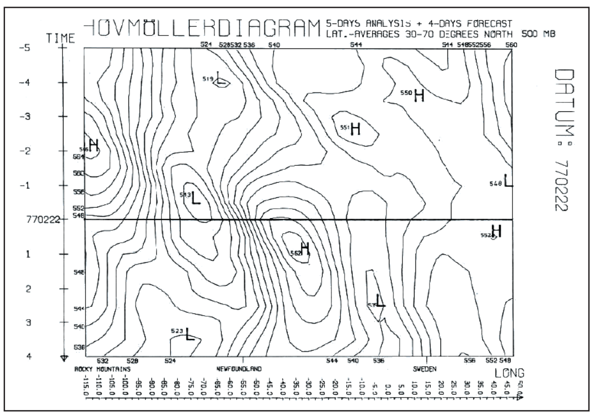

Figure 4: A "Hovmöller Diagram" plotted at SMHI in the late 1970's, covering the preceding five days (17-22 February 1977) and the following four days (22-26 February 1977) according to the NWP at SMHI. The parameter was 500 hPa geopotential, the latitude interval between 70° and 30° N and the longitude ranged from 115° W to 50° E. A strong "downstream development" is seen passing from the western to the eastern hemisphere.

When I attended my first ECMWF training course in 1983 (as a student) I became aware that at about the same time, in the late 1970's, three young British meteorological scientists at Reading University, had brought "downstream development" back into the theoretical fold after 20 years of absence. They appealed to this concept in trying to understand numerical experiments on baroclinic instability and, in particular, the triggering of successive baroclinic waves (Hoskins, Simmons and Andrews, 1977). This and other papers by them could have stimulated further research, but soon after **Adrian Simmons** had left for ECMWF and **Brian Hoskins** was heading towards new theoretical challenges.

The interest in "downstream development" might have faded again if it hadn't been for a series of papers in the late 1980's and early 1990's by the American meteorologist **Isodoro Orlanski.** He had set out to study how strong cyclogenesis in the southern hemisphere affected the "ozone hole". But his energy calculations for the cyclones did not "add up" unless he also included the energy import from the next upstream cyclone. With his student **Edmund Chang**, they (see e.g. papers by Orlanski and Chang in the literature list at the end) depicted this in Hovmöller diagrams, not with the mean meridional geopotential of the mid-tropospheric flow but with the mean meridional wind component of the upper tropospheric flow, as first suggested by Carlin (1953).

In figure 5 we can on one hand see ridges and troughs moving eastward at about 10°/day. But more striking to the eye are the occurrences of "downstream development" which progress at about 30°/day. The figure also gives a clue to what is "going on": *a rapid transport of energy downstream*.

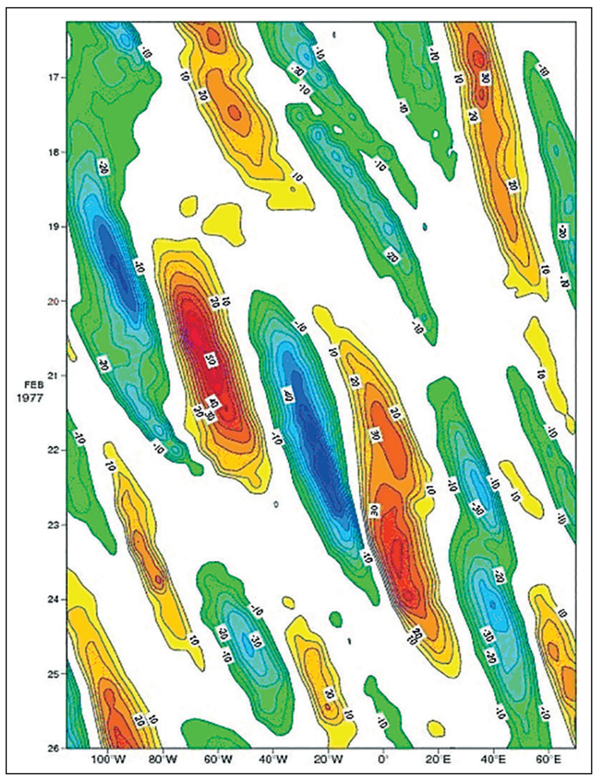

Figure 5: A modern version of the Hovmöller Diagram for the same period in February 1977 as depicted in figure 4. Instead of 500 hPa geopotential values the average 250 hPa meridional wind vector is used. Negative v-values (northerly winds) are in green and blue, positive v-values (southerly winds) in yellow and red. The latitude interval is 30° to 50° N. A second, weaker «downstream development» is seen starting on 22 February a couple of days after the first starting on 19 February.

The trough-diagram enters ECMWF

When I joined the ECMWF in 1992 my manager, **Bernard Strauss**, asked me to come up with some new ideas for the map room. I suggested a daily display of a Hovmöller Diagram based on 20 days retrospective analyses and the 10 days forecast. This was quickly accomplished with the help of **Bruno David**. By consulting Ernest Hovmöller himself over the phone (by then 80 and still living in Sweden) it was decided to use the Swedish spelling with "o" of his name and not the Danish with "ø".

Since we at that time were unaware of Orlanski's and Chang's work, our diagram became the traditional one based on 500 hPa geopotentials. But when we became aware of their work Bruno David quickly developed a program to produce "Orlanski-Chang diagrams" as batch jobs. They were presented at the training courses because they more clearly than the traditional "Hovmöller diagram" displayed what is the cause of the "downstream development" process.

Like Rossby, I had not been satisfied with the common mathematical-algebraic or geometrical-kinematic explanation, but tried to find a physical-dynamical one. The "Orlanski-Chang diagrams" provided that and did so without introducing any new "alien" concepts.

Energy propagation

Figure 6 shows a typical jet stream. We know that the isotach pattern normally moves eastward, with the zonal flow, with about the same speed as the baroclinic system it is coupled to. This is also how it is treated in standard quasi-geostrophic theory.

The lower part of the picture, with the wind vectors, shows how the wind at the entrance of the jet (to the west) is moving down gradient while increasing its velocity. Potential energy is thereby transformed into kinetic and the geopotential gradient is weakening. When the wind has reached its maximum velocity, at the core of the jet stream, it is moving almost parallel to geopotential isolines.

It is important to realize that the wind moves much faster than the isotach pattern; *the wind is blowing "through" the jet stream*. When it approaches the exit of the jet stream (to the east) it is super geostrophic, i.e. stronger than the geostrophic wind. It means that the Coriolis force on the air parcels is stronger than the pressure gradient force and the wind is therefore accelerated to the right, up-gradient. This *up-gradient* transport leads to a sharpening of the geopotential gradient, potential energy is increasing at the same time at the expense of kinetic as the wind is slowing down.

This means that energy has been rapidly transported though the jet stream much faster than the synoptic systems have progressed eastward. If the condition close to the exit region is favourable for a new baroclinic development, it will take place, supported by the arrival of "extra energy" - *the first link in the downstream development chain has developed*!

Simplified images

In a theoretical paper by Brian Hoskins et al (1983) dealing with something similar, "wave activity", we find a nice, although simplified, image of this process, the "hand over" of kinetic energy from one cyclone to the next downstream (figure 7). What is missing in the picture is the conversion between potential and kinetic energy.

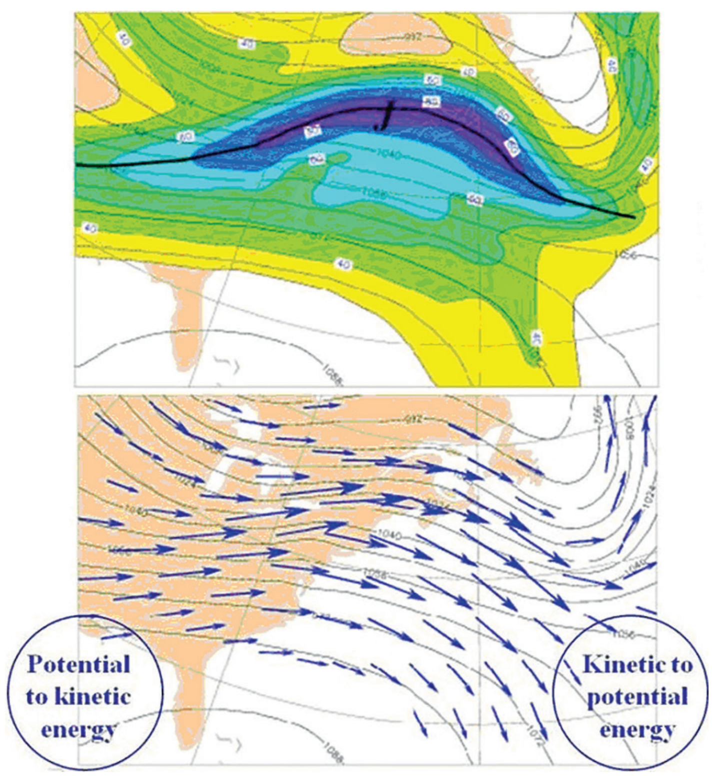

Figure 6: A typical upper tropospheric jetstream presented both in terms of isotachs (upper figure) and wind vectors and geopotentials (lower figure).

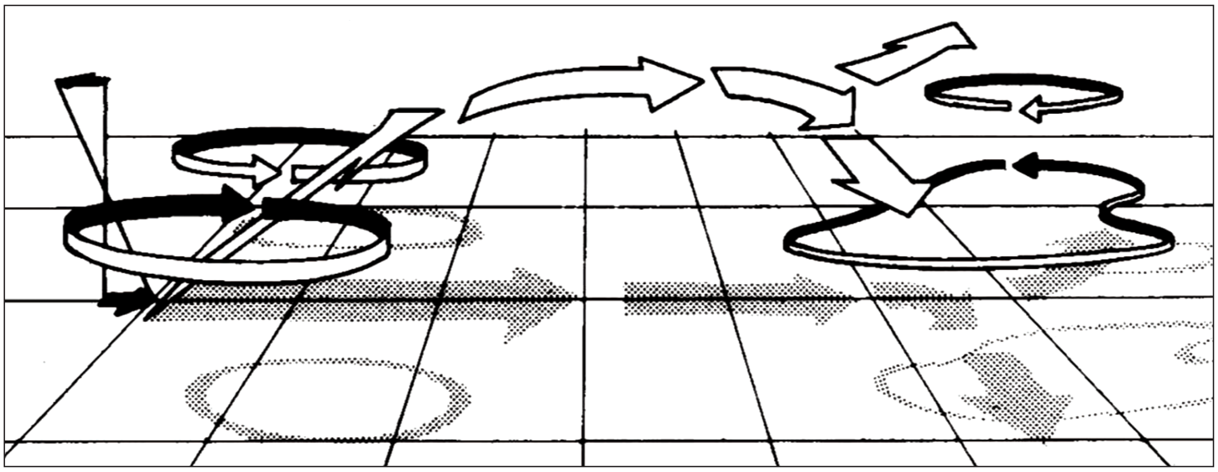

Figure 7: The concept of released kinetic energy rapidly transported downstream with the upper tropospheric flow has been nicely depicted in Hoskins, James and White (1983) although the terminology there is in terms of "wave activity".

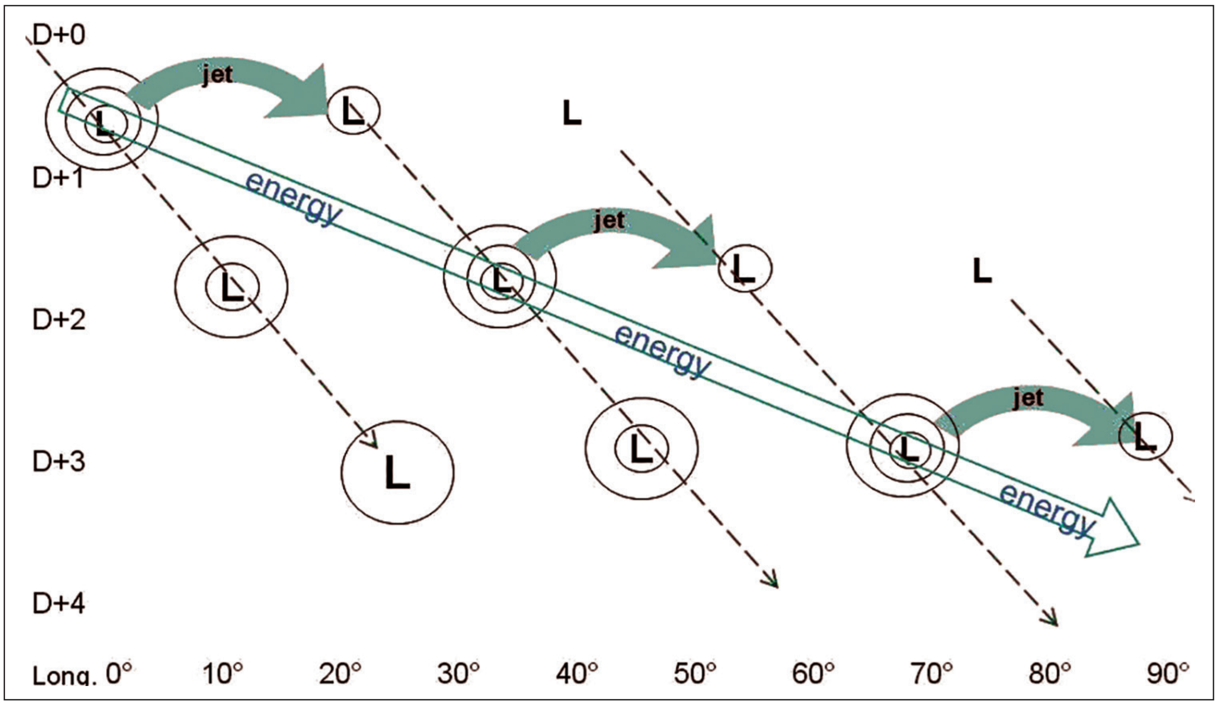

Figure 8: A schematic view of a downstream development process over three-four days covering a west-east section of 90-100 longitude degrees. See text for more details

A seminal paper by Orlanski and Sheldon (1995) contains two very instructive figures (2 and 3) with the same message: the propagation of energy from one system to the next downstream. Below is my attempt to conceptualize the process (figure 8).

On the first day a cyclone is deepening while moving downstream at about 10°/day. During its deepening, potential energy is converted into kinetic which is seen both in the winds in the lower troposphere (leading to "gale warnings"), but also in the upper troposphere (the "jet stream").

Non-forecasting applications

There is much more to say about "downstream development" or "group velocity thinking", but this article is already too long. This concept has played a major role in attempts to trace the origins of bad forecasts, when that is due to poor initial conditions. The reverse problem, about introducing new observations in order to improve a forecast, is also based on "group velocity thinking". Finally, the dynamics of ensemble forecasts where thousands of "butterflies" are inserted into a basic analysis also need "group velocity thinking" to be properly understood.

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