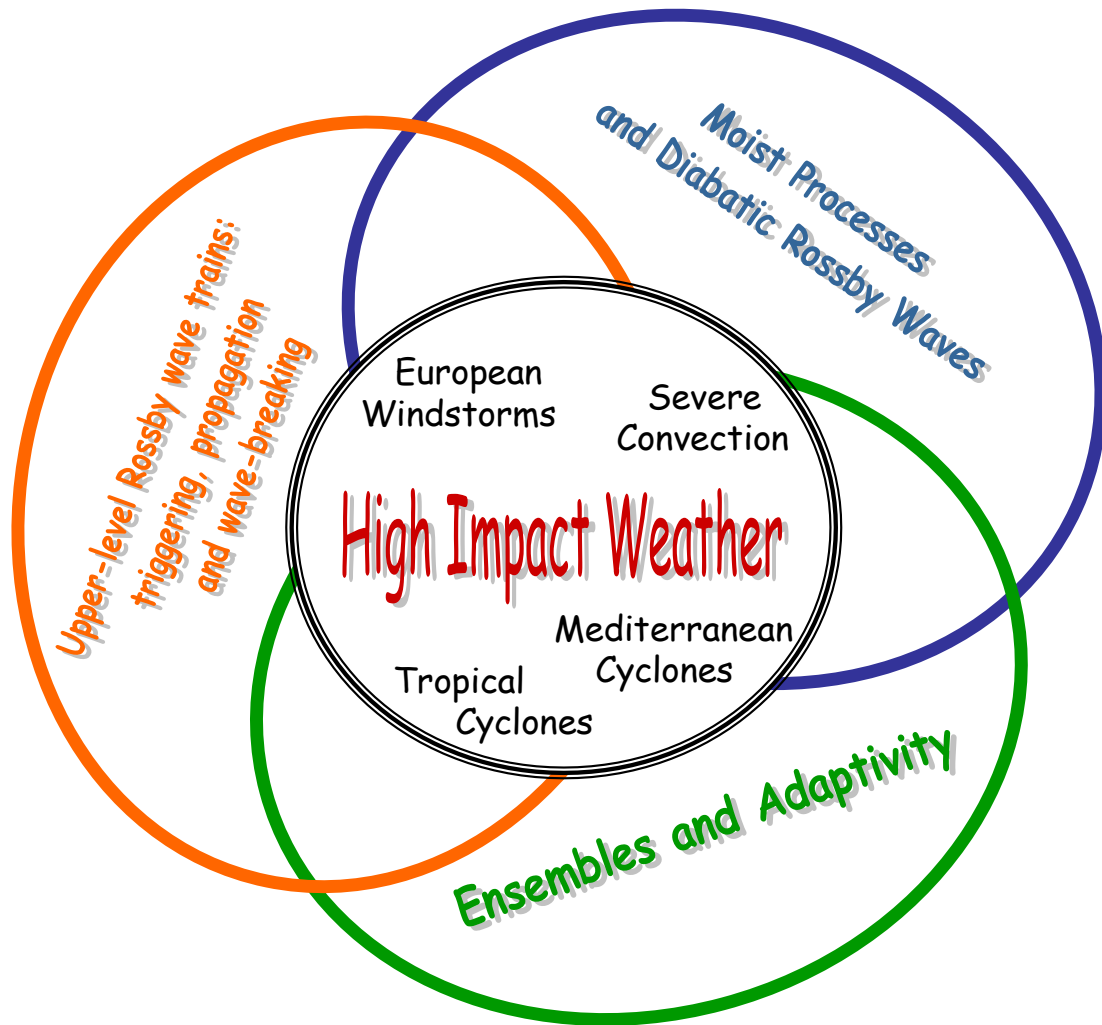


Predictability **ANd** Dynamics Of **W**eather Systems in the **A**tlanctic-**E**uropean Sector



PANDOWAE

Deutsche Forschungsgemeinschaft (DFG) Research Group

FOR896

Summary

The aim of the research group PANDOWAE is to advance our knowledge and understanding of the dynamical processes responsible for the development of high impact weather systems, to elucidate the factors that limit the predictability of such systems, and to contribute the basic research that will lead to the development of innovative interactive weather forecasting systems.

The project will be divided into three research areas. Current research has indicated that upper-level Rossby wave trains play an important role in the sequential initiation of high-impact weather events around the globe. Significant gaps exist in our knowledge of the processes responsible for the initiation of Rossby wave trains, their propagation and subsequent wave-breaking. In the first research area we will address questions concerning these factors, their representation in numerical weather prediction models, and their role in the initiation of high impact weather. Moist processes play a crucial role in the development of almost all severe weather systems. In the second research area we will quantify their contribution both to a variety of individual systems and in a climatological sense and assess the importance of moist processes in the growth of errors in numerical forecasts. Moisture plays an intrinsic role in the initiation of diabatic Rossby waves. The physics of these recently recognised and incompletely researched phenomena differs fundamentally from that of traditional Rossby waves. Diabatic Rossby waves develop and propagate due to the generation of potential vorticity by cloud condensational processes and have been linked to the development of severe winter storms. Many fundamental questions remain unanswered as to how often diabatic Rossby waves occur, their importance in the development of severe weather, and the ability of operational models to predict them. The final research area will underpin innovative developments in numerical weather prediction by contributing through basic research to the development of adaptive observing strategies and to the new generation of adaptive ensemble forecasting systems.

In PANDOWAE, expertise in the three individual research areas will be brought together to study the dynamics and predictability of high impact weather systems. The collaboration between the different experts will enable us to move forward in this area in a way that would not be possible for individual investigators studying aspects of the problem in isolation. PANDOWAE represents an important German contribution to the ten year international research programme of the World Meteorological Organisation *THORPEX: a World Weather Research Programme*. Through collaboration with operational weather services, in particular with the Deutscher Wetterdienst and the European Centre for Medium-Range Weather Forecasts, PANDOWAE will achieve one of the aims of THORPEX to promote cooperation between academic institutions and operational centres. Furthermore, PANDOWAE will provide a framework to bring young researchers to the forefront of world weather research.

Progress will be made through investigations with operational analyses, forecasts, and reanalyses, through using operational data assimilation systems to investigate the utility of particular datasets and observing systems, and through using numerical models and a variety of diagnostic techniques. PANDOWAE researchers will be amongst the first to use the newly-available database of the THORPEX Interactive Grand Global Ensemble (TIGGE). They will conduct studies with high resolution limited area models, with global operational forecast models and with global and limited area ensemble prediction systems, as well as using idealised modelling studies to investigate individual processes. This powerful use of operational tools in a basic research context will promote ground-breaking research that will be translated ultimately into improved weather forecasts for the benefit of society, the economy and the environment

1. Rationale

Accurate numerical weather forecasts are essential for the mitigation of the threat to life and property presented by high-impact weather systems. In Europe a variety of different systems present significant challenges for numerical weather prediction. These include winter storms such as Lothar (1999) and Kyrill (2007), Mediterranean cyclones, flooding events such as the Elbe flood of 2002, mesoscale convective systems with associated severe gusts, hail and heavy precipitation, storm surge in the North Sea and Baltic Sea, and heat waves as in the summer of 2003. The majority of these high impact weather events that threaten western and central Europe, while often small in scale, owe their development to larger scale motions. In the Atlantic-European sector the structure of the upper-tropospheric jetstream plays a crucial role in the development of European high impact weather. Significant North-South excursions of the jet can promote explosive extratropical cyclogenesis, trigger severe convection, or steer tropical cyclones into the midlatitudes. A strong but zonally-oriented jet with the associated low-level baroclinic zone provides the necessary conditions for the development of diabatic Rossby waves. The strong horizontal and vertical shear of the jet is important for the excitation of gravity waves or the development of instability resulting in clear air turbulence.

A significant role in the development of severe weather is played by Rossby wave trains that propagate on potential vorticity (PV – Ertel 1942) gradients such as associated with the upper tropospheric jetstream. Some of the triggers of Rossby wave trains are organised tropical or extratropical convective systems, extratropical cyclones, and the interaction of extratropical flows with topography. At a latitude of 45°N Rossby wave trains can circumnavigate the hemisphere in about 12 days. Amplified Rossby waves can themselves initiate extratropical cyclogenesis and moist convection. Breaking Rossby waves can excite inertia-gravity waves that cause clear air turbulence and, if they propagate downwards into the lower troposphere, may initiate convective storms.

Moist processes play a fundamental role in most severe weather events. The modification of the atmospheric stability by moisture is crucial for the development of severe convective storms. The transport of moisture from the tropics into the midlatitudes can create an environment favourable for explosive cyclogenesis or heavy precipitation events. Local evapotranspiration can intensify the aforementioned phenomena. Moist processes are an essential part of tropical cyclones that may develop into extratropical systems and initiate explosive downstream cyclogenesis. The interplay between lower-tropospheric PV anomalies and moist processes can lead to latent heat release in frontal regions or convection over the ocean. One consequence of this interaction is the initiation of diabatic Rossby waves in the lower troposphere that can interact with upper-tropospheric features leading to the development of wind storms such as “Lothar”.

Despite significant improvements in numerical weather prediction there is still large uncertainty in the forecast of high impact weather events that are often associated with small-scale, rapidly-developing features in which moist processes are crucial. Fundamental predictability studies established that the growth in uncertainty can be attributed to the two-way-cascade of energy and enstrophy between planetary-scale circulations that act to organise synoptic- and mesoscale flows, and small-scale and frequently unresolved perturbations (e.g. moist convection, inertia-gravity waves) that influence the large-scale motions. The interaction between polar/arctic weather systems and the midlatitude flow is a further source of forecast error. Predictability for Europe on a time-scale of several days to two weeks is frequently and in cases strongly influenced by tropical-extratropical interaction and in particular by tropical convection and tropical cyclones. In the Atlantic, tropical convection and cyclogenesis in the Caribbean and Gulf of Mexico or the presence of a tropical cyclone off the east coast of North America can lead to significant errors in the medium-range forecast for western Europe. Errors in the 5-15 day forecasts can frequently be traced back to the tropical Pacific. Furthermore, extratropical cold surges and upper-level cut-off lows can excite tropical convection or play an instrumental role in tropical cyclogenesis, thus influencing predictability for the tropical Atlantic.

Traditional numerical weather forecasts have provided a single forecast from a given initialisation time – often referred to as the deterministic forecast. Given the inherent uncertainty in both model and initial conditions ensemble prediction systems are becoming

increasingly important in order to provide information about the probability of a given forecast scenario. For both deterministic and ensemble forecasts the best possible representation of the initial conditions requiring optimal use of the global observing system is a prerequisite for a useful forecast. This leads to the concept of adaptive observations, in which the observations are optimised in order to produce the best possible numerical forecast. The development of adaptive observing strategies and ensemble forecasting systems requires innovative research into the predictability of weather systems. The utility of new observing systems, the best usage of current observing systems, and the optimal ensemble configuration must be considered and related to the knowledge of individual weather systems.

In order to improve prediction of high impact weather in the Atlantic-European sector we must improve our basic knowledge of the global to regional influences on the evolution and predictability of high impact weather. Gaps in our knowledge exist associated with ultra-long waves that have a significant influence on the background flow, the excitation and dispersion of near-tropopause Rossby wave trains and diabatically driven propagating PV anomalies, and the mechanisms that determine their role in the initiation and/or intensification of extratropical cyclones or the creation of flow patterns conducive to the development of heavy precipitation events.

THORPEX: a world weather research programme is an international research programme under the auspices of the WMO World Weather Research Programme. It aims to accelerate improvements in the accuracy of 1-day to 2-week weather forecasts for the benefit of science, society and the economy. This aim will be achieved through international collaboration and cooperation between academic institutions and operational forecast centres. THORPEX is organised thematically into four sub-programmes. This project represents a significant contribution to THORPEX Predictability and Dynamical Processes (PDP) research whose aims are “to assess the various factors that contribute to current limits of predictability for appropriate forecast attributes, and through this determination, develop and demonstrate new dynamical interpretations, and observing systems and forecasting strategies that will extend these limits”.

The DFG research group PANDOWAE represents a strong German contribution to THORPEX. The focus on fundamental research in PDP through the expertise present in PANDOWAE will allow us to gain knowledge of the factors that limit predictability through basic research. Contributions to the Data Assimilation and Observing Strategies (DAOS) sub programme will provide information to improve the initialisation of forecast models and design the future observing system. The infrastructure of THORPEX will enable the transition of this knowledge into operational forecasts. The 6 year perspective given by a DFG research group fits well with the 10 year timeframe of THORPEX and will allow advances made internationally in other areas of THORPEX to feed back into PANDOWAE research. Furthermore, THORPEX provides new opportunities for collaboration between operational centres and academic institutions and these will be exploited within PANDOWAE.

2. Background

2.1 High impact weather in the Atlantic-European sector

The focus of this project is high impact weather that occurs in the Atlantic and over western and central Europe, including the Baltic Sea and Mediterranean regions. Priority will be given in particular to the following.

2.1a European windstorms

Windstorms in Europe occur mainly in autumn and winter. They are typically associated with the passage of intense extratropical cyclones and/or their frontal systems. During the last 20 years, the probably most damaging storms were the 1987 October storm in the UK and France (Burt and Mansfield 1988), the December 1999 Denmark storm (Nielsen and Sass 2003) the two successive storms in December 1999 over central Europe (Lothar and Martin, Ulbrich et al. 2001) that led to enormous damage in France, southern Germany and Switzerland and Kyrill (January 2007) that caused damages in excess of 2 Billion Euro in

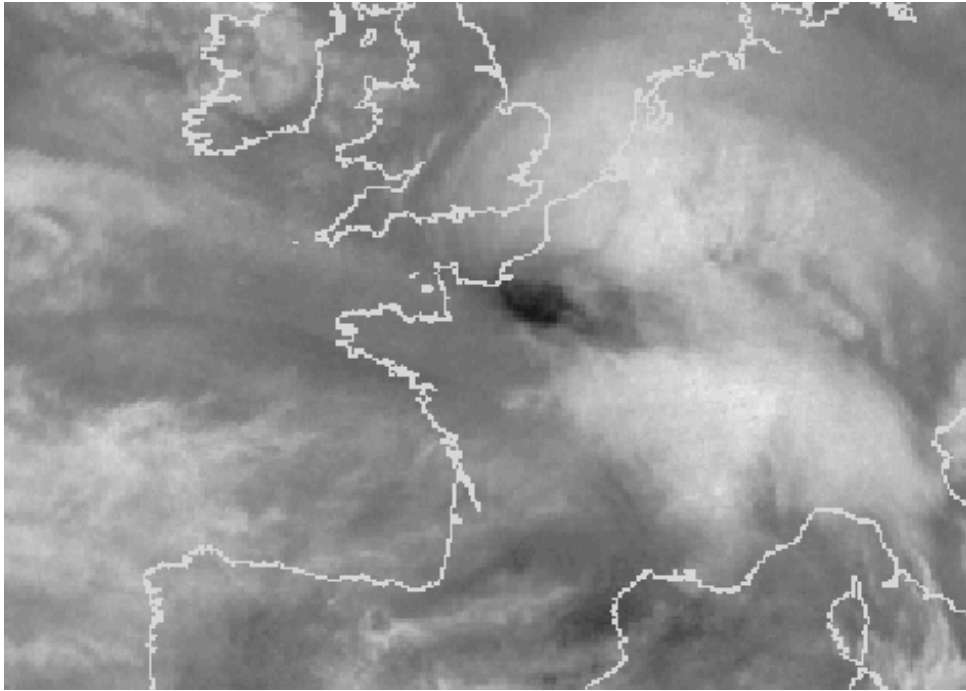


Figure 1: Water vapour satellite image of "Lothar" at the time when the storm passed over Paris. The dark spot corresponds to the rapid formation of a tropopause fold triggered by the bottom-up effects of a low-level diabatic Rossby wave.

Germany alone and brought the German railway system to a total standstill for the first time in history. With the exception of Kyrill these examples of extreme European winter storms were poorly forecast. Kyrill was very well forecast with more than 24 hours lead time so that timely warnings could be delivered to emergency managers and the general public. However, even in this case the current operational forecast models did not completely provide the detailed structure of Kyrill necessary for the efficient guidance of local emergency response staff. All of these storms were associated with particularly strong diabatic processes and intense precipitation and were characterized by a different dynamical evolution. The storms over the UK and Denmark were interpreted as a consequence of favourable interaction between upper and lower-level potential vorticity anomalies (Hoskins and Berrisford 1988; Nielsen and Sass 2003). In contrast, the hypothesis for the explosive development of the "Lothar" storm was a bottom-up development induced by a diabatic Rossby wave below a straight and intense upper-level jet without a notable precursor disturbance at the tropopause level (Wernli et al. 2002). This subtle difference in the basic dynamical evolution is interesting and points to the existence of different mechanisms that lead to explosive cyclone development, and to potential forecast failures. The storms described above highlight also the challenge involved in the prediction of such systems, since their evolution depends crucially on mesoscale structures over the generally data sparse oceans, both at the level of the tropopause (wind, temperature) and in the lowest troposphere (also humidity).

2.1b Mediterranean cyclones

Both heavy rain and strong winds lead to severe impacts in the Mediterranean region. The majority of these events occur in late summer and autumn and are associated with cyclones (Jansa et al. 2001). These cyclones may be shallow orographically induced features, or may develop due to strong upper-level forcing associated with stratospheric PV streamers. Furthermore, small-scale hurricane-like systems (Medicanes) may develop in the centre of an upper-level cold low. The autumn timing of most severe weather events in the Mediterranean emphasises the importance of the warm moist Mediterranean air mass at low-levels. The main physical contributors to Mediterranean cyclogenesis are orography, sea surface temperature, surface heat fluxes, latent heat release, convection, baroclinicity and

the intensity of an upper-level precursor (Buzzi et al. 2005). The complex interaction between these processes presents a challenge to operational forecast models.

The development of cyclones over the western Mediterranean especially in late autumn is often associated with heavy-rain events in south-eastern France and northern Italy (Pinto et al. 2001). Large scale lifting combined with embedded convection and intensified by the orography may cause flash floods in the narrow mountain valleys due to rainfall of more than 300 mm in 24 hours. The heavy-rain events are the results of combined advective and convective water vapour transport processes (Pytharoulis et al. 2000). In the last decade at least one cyclone per year caused enormous damage and losses of human lives by floods in that specific area (Table 1). The interaction of precipitation creating processes on different scales such as synoptic-scale forcing of ascent and small scale convection triggered by surface processes leads to problems in forecasting the precipitation by numerical models. In addition, a recent study (Homar et al. 2006) indicates a need for more observations over the eastern Atlantic and North Africa in order to improve forecasts of Mediterranean cyclogenesis.

Episode	Country	Date	Max. precipitation in 24 hours
Vaison-la-Romaine	France	22.-23. 09. 92	300 mm at selected sites
Brig	Switzerland	23.-25. 09. 93	120 mm (23.09), 220 mm (24.09.)
Piedmont	Italy	04.-06. 11. 94	314 mm, 250 at several sites
Ticino	Italy	12.-13. 09. 95	186 mm in 12 h, 327 mm in 36 h
Friuli	Italy	19. 09. 95	180 mm
Friuli	Italy	05.-07. 10. 98	~ 250 mm in 48 h
Thyrrhenian Sea		26.-27. 03. 99	

Table 2: Severe cases of Mediterranean cyclogenesis associated with heavy flash floods

2.1c Tropical cyclones and their transformation into extratropical systems

Tropical cyclones are responsible for some of the most severe weather impacts in the Atlantic. Their direct impact on land as a tropical system is confined almost entirely to the western Atlantic, although in an active year such as 2005 southern Europe can be affected by weak tropical cyclones (Vince made landfall in Spain, Delta in the Canary Islands). A more significant threat for Europe is presented by those systems that interact with the midlatitude flow and undergo extratropical transition.

When a tropical cyclone moves polewards it interacts with the midlatitude flow such that it undergoes significant structural characteristics and may transform into an extratropical weather system (Jones et al. 2003 and references therein). Transformed tropical cyclones that reach Europe can still result in severe weather (e.g. ex-Hurricane Lili in 1996), but these events are relatively infrequent. Arguably a more significant threat for Europe is posed by the excitation of a Rossby wave train as a tropical cyclone interacts with the midlatitude flow

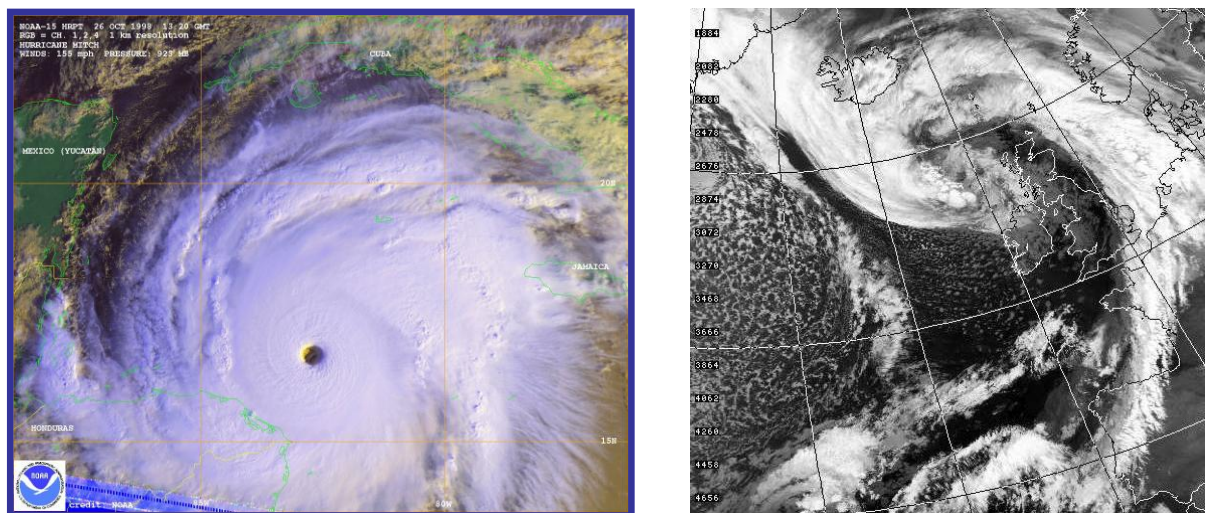


Figure 2: Satellite image of Hurricane Mitch (1998) in the Caribbean (left) and the extratropical low that developed from Mitch north of Scotland (right).



Figure 3: Severe convection on 11 June 2007 during the COPS (Convective and Orographically-induced Precipitation Study) experiment. Top: The approach from the right of a severe thunderstorm with heavy precipitation. Bottom: A thunderstorm in its development stage.

(hereafter downstream impact). Hoskins and Berrisford (1988) attributed the development of a tropopause step that was crucial for the development of the October Storm in 1987 to the outflow from Hurricane Floyd (1987).

Numerical weather prediction for tropical cyclones has considerably lower skill than for their midlatitude counterparts. As a tropical cyclone moves into the midlatitudes the combination of the large uncertainty in the tropical cyclone position and intensity and errors in the representation of the midlatitude flow frequently result in poor forecasts of extratropical transition. This can lead to a reduction of the skill averaged over a whole ocean basin (Fig. 8 in Jones et al. 2003). The impact of extratropical transition on the predictability of the downstream flow is more difficult to quantify. However, forecasters in European operational weather centres associate the presence of a tropical cyclone in the western Atlantic with large forecast errors and inconsistency between consecutive forecast times. Furthermore, in

a recent study Cardinali et al. (2007) found that targeted observations had a greater impact on the forecast during an extratropical transition event.

2.1d Severe convection in Europe

Severe convection is responsible for a significant fraction of weather-related loss of life and property in extratropical latitudes (Pielke and Klein 2001; Fritsch and Carbone 2004). The most important precondition for convection is an unstable environment, usually associated with tropospheric cooling as a result of ascent driven by the synoptic flow (e.g. Roberts 2000). This indicates that an accurate forecast of the large-scale weather systems can provide valuable information about the occurrence of convection, however, the convective systems themselves are typically tens of kilometres in size with lifetimes measured in hours – a precise forecast at that scale would require observations at impracticably high density and even then would lose accuracy in less than a day.

It is generally conceded that convection is forecast badly at present, but the limits of predictability for convection are not known (Ebert et al. 2003). Significant gains have been obtained in recent years from high resolution forecasting systems, but these will be ultimately limited by chaotic nature of the storms on relatively short timescales (Walser et al. 2004). Ultimately, the most valuable forecast is likely to be probabilistic, taking account of the uncertainties in both the large and small scale processes, but progress in designing an optimal forecasting system is limited by a lack of understanding of the roles and interactions of the various scales of atmospheric motion involved in the initiation of a convective event (Fritsch and Carbone 2004).

2.2 Research Areas

A number of common factors can be identified that influence the development and structure of the high impact weather systems described in section 2.1. In many cases the environment in which they develop is determined by the synoptic- to planetary-scale framework associated with upper-level Rossby waves. Moist processes play a fundamental role in the development and structure of the systems as well as in their impact on the large-scale flow. The uncertainty associated with forecasts of these systems is such that the use of ensemble forecasts and adaptive observing strategies is expected to improve the information contained in forecasts. Thus PANDOWAE research will focus on 3 research areas, the background of which is given in this section.

2.2a Upper-level Rossby wave trains: generation, propagation and wave-breaking

Synoptic-scale Rossby waves play an important role in the transport of heat and momentum between subtropical and polar regions both in the troposphere and the lower stratosphere. They are associated with transport of ozone, water vapour, and other trace species, and they have a significant impact on troposphere-stratosphere exchange. Rossby waves are responsible for links between different locations (“teleconnections”), and the interaction between transient Rossby waves and the quasi-stationary wind field have a strong influence on the position of storm tracks (e.g. Hoskins et al. 1983; Trenberth 1991). Rossby waves develop and propagate on the underlying background PV gradient. The simplest manifestation of a Rossby wave is a synoptic-scale perturbation of an isentropic PV contour near the tropopause.

Rossby wave trains are spatially-confined superpositions of Rossby waves centred about a dominant wave. Like Rossby waves, Rossby wave trains can propagate over long distances (Fig. 4; Langland et al. 2002). They are generated by a variety of processes, about which our present knowledge is incomplete.

Theoretical studies and idealized numerical experiments indicate that topographically and diabatically-generated vortex anomalies at upper and lower levels can serve as triggers for Rossby waves (Sardeshmukh and Hoskins 1988; Bell 1990; Schwierz et al. 2004). In particular, case studies and trajectory analyses have shown that diabatic processes play a significant role in shaping the wave-guide and the amplification of the waves (Massacand et al. 2001). Advection by the circulation of upper-level lows can also perturb the PV gradient and trigger Rossby waves.

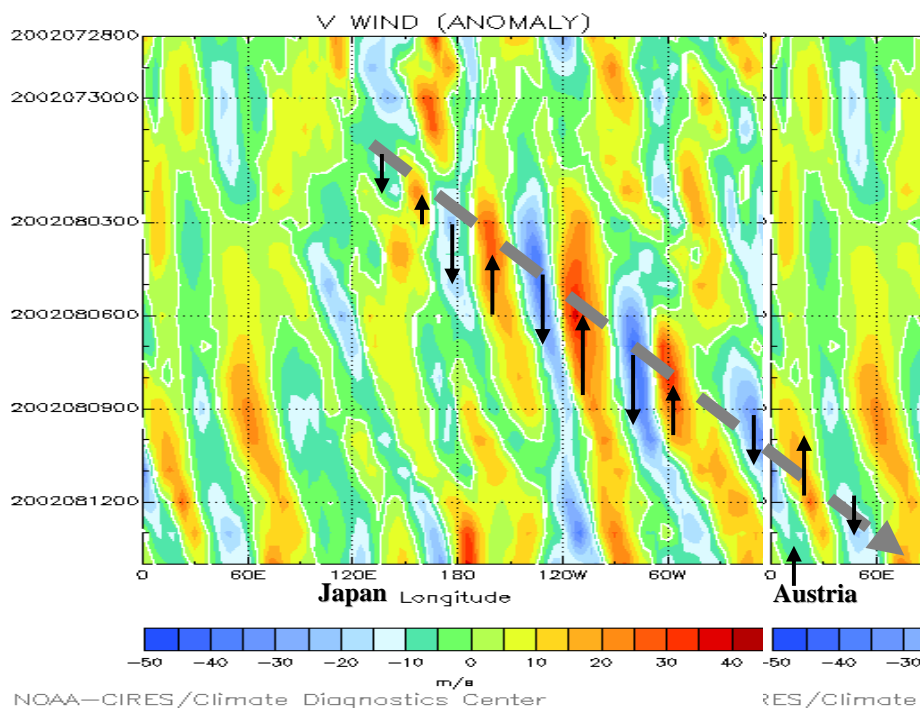


Figure 4: Hovmöller plot of 250 hPa meridional wind from 28 July – 14 August 2002 averaged from 40°–60° N. The Rossby wave train indicated by the dashed arrow was initiated by cyclogenesis east of Japan, and developed downstream resulting in severe flooding in Europe on 11 August 2002. Taken from the THORPEX International Science Plan.

Rossby wave propagation depends crucially on the background flow, linked to the strong PV gradient associated with the jet stream at the tropopause (Rossby 1940; Bell 1990). The latitudinal and longitudinal variations in the basic flow structure strongly influence the characteristics of Rossby wave propagation. The intrinsic phase propagation of Rossby waves is westward against the basic flow. In the absence of critical lines Rossby wave trains may travel over long distances determined by their wave-guides. The vertical and horizontal propagation is restricted by critical wind lines (e.g. Magnusdottir and Haynes 1996), exhibits a strong seasonal variability, and influences the evolution of baroclinic life cycles (Davies et al. 1991; Thorncroft et al. 1993).

Following an initial phase of linear wave growth and propagation, Rossby waves may reach a phase of nonlinear saturation, followed by wave breaking. This is indicated by a reversal of the latitudinal PV gradient. The wave breaking phase is characterized by an irreversible mixing of air masses (PV contours) due to turbulent processes in the breaking zone (McIntyre and Palmer 1983).

Breaking Rossby waves are a frequent phenomenon in both hemispheres (Norton 1994; Peters and Waugh 1996; Appenzeller et al. 1996; Peters and Waugh 2003). Four typical cases of Rossby wave breaking events have been identified downstream of a dominant jet stream: equatorward breaking in anticyclonic / cyclonic shear and poleward wave breaking in anticyclonic / cyclonic shear (e.g. Esler and Haynes 1999). Poleward breaking events appear very often over the North Atlantic-European region in wintertime (e.g. Peters and Waugh 1996). Furthermore, strong moisture transports, ozone anomalies and enhanced excitation of inertia-gravity waves are linked to the phenomenon of poleward breaking Rossby waves (Zülicke and Peters 2006).

Rossby wave breaking indices have been defined based on the latitudinal PV gradient using visual inspections, on specific objective measures (e.g. Postel and Hitchmann 1999, Waugh and Polvani 2000, Walker and Magnusdottir 2003), or by using the meridional flux of wave activity (Esler and Haynes 1999). Yet other approaches use a feature-based methodology that detects the elongation of the isentropic 2 PVU contour. Both the contour elongation itself (Martius et al. 2006a) and the subsequent formation of narrow filaments

(Wernli and Sprenger 2007; Martius et al. 2006b) can be diagnosed and interpreted as indicators for Rossby wave breaking. Gabriel and Peters (2006) defined a Rossby-wave-breaking index combining the meridional flux of wave activity and the diffuence/confluence of the large-scale flow, which successfully indicates preferred regions of poleward breaking Rossby waves in wintertime.

Upper-level Rossby wave breaking, the formation of PV streamers and their interaction with the surface baroclinic zone play a crucial role in the development of extratropical cyclones (Petterssen and Smebye 1971; Hoskins et al. 1985; Langland et al. 2002) and the occurrence of severe precipitation events (Massacand et al. 1998; Martius et al. 2006b). A recent example is the Elbe flooding case of August 2002. Preliminary analysis (Grazzini and van der Grijn 2002) has shown that this particular event of extreme precipitation was associated with an unusually long-lived Rossby wave train and related downstream development. Although the European Centre for Medium-Range Weather Forecasts (ECMWF) forecasts contained some elements of this wave train, they missed other key features.

The predictability of high impact weather is closely related to the ability of numerical models to represent upper-level Rossby waves. It has been shown that model errors propagate in a similar manner to Rossby waves (Langland et al. 2002). The correct phasing and orientation of the streamers- and hence the location of the severe weather event - still pose significant problems for current prediction models (Dirren et al. 2003). Extreme poleward breaking events may have a large influence on the weather over Northern Europe. A particular forecasting challenge arises when linkages of the Rossby waves and PV streamers with tropical systems have to be considered. It is observed frequently that the presence of an extratropical transition system on the western side of an ocean basin is associated with a period of low predictability downstream (Harr et al. 2007; Anwender et al. 2007).

2.2b Moist processes and diabatic Rossby waves

It is well established that diabatic processes (cloud condensational heating and surface heat fluxes) that occur in extratropical cyclones generally increase the deepening rate (Uccellini 1990). Several case studies have shown that most cyclones develop primarily due to dry dynamics (baroclinic instability), but that diabatic processes enhance their final intensity (e.g. Kuo et al. 1991, Rossa et al. 2000). As a consequence, diabatic processes play a crucial role in the dynamics of particularly severe storms. However, a systematic climatological study of the relationship between cyclone intensity and associated diabatic processes is lacking. Also, it is not clear, how often and to what degree moist processes (e.g. errors in low-tropospheric humidity) contribute to forecast failures.

When studying the dynamics of the explosive winter storm “Lothar”, Wernli et al. (2002) suggested that the early phase of this cyclone resembles the concept of a diabatic Rossby wave. These are positive low-tropospheric PV anomalies that are steadily regenerated by condensational processes in a baroclinic environment. In a diabatic Rossby wave heating can act as a surrogate for large-scale PV gradients (Snyder and Lindzen 1991). The basic mechanism can be described in 3 stages (e.g. Parker and Thorpe 1995). The main ingredients are (i) an intense and relatively straight baroclinic zone, (ii) sufficient moisture at low levels on the warm side of the baroclinic zone, and (iii) a pre-existing positive low-level PV anomaly. The circulation induced by this anomaly advects warm and moist air towards the colder side of the baroclinic zone where it rises along the sloping isentropes. The moist air saturates quickly and latent heat release due to condensation sets in. Diabatic PV modification (e.g. Wernli and Davies 1997) leads to the production of positive low-level PV directly downstream of the original PV anomaly. This wave-like process of continuous PV regeneration due to condensation leads to a rapid downstream propagation of the vortex that exceeds the mean flow speed at this level. Moore and Montgomery (2004, 2005) showed that diabatic Rossby waves can grow as a result of an approximate phase-locking and mutual amplification of a positive low-level and a negative mid-tropospheric PV anomaly, both generated diabatically. Open questions here are related to the frequency of diabatic Rossby waves and the general quality of their prediction by global and regional models.

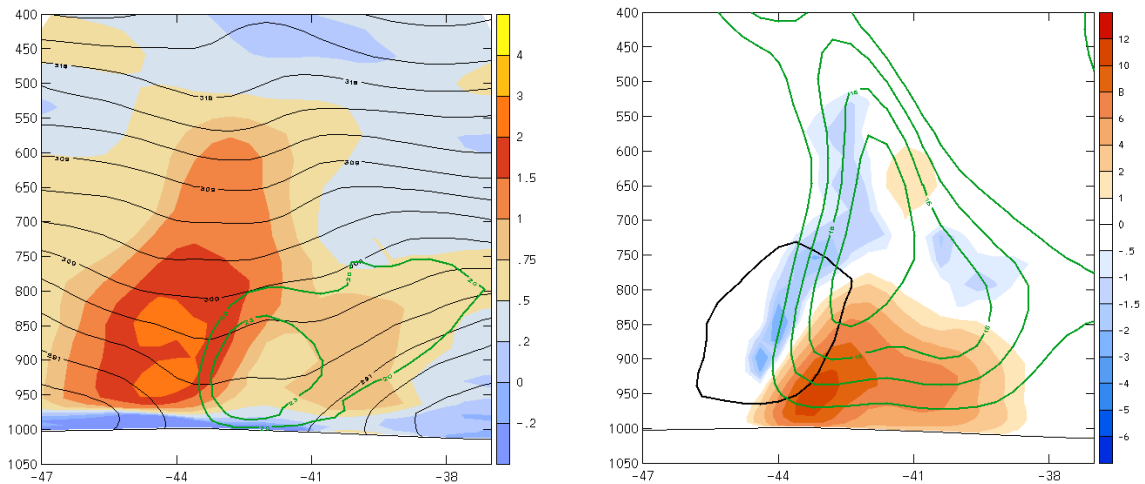


Figure 5: West-east oriented vertical sections across diabatic Rossby wave associated with the early phase of "Lothar". Shown are (left) the PV field (colors, in pvu), potential temperature (thin lines, every 3 K) and two bold contours for 20 and 23 m/s southerly wind, and (right) vertical velocity (green contours, in cm/s, only ascending motion is shown), the 1.5 pvu contour (black line) and the diabatic PV rate (colors, in pvu/h). Together the diagrams illustrate the DRW propagation mechanism with diabatic PV production downstream of the existing low-level PV anomaly.

Despite the similar name, diabatic Rossby waves are fundamentally different to upper-level Rossby waves. The physical principle of the latter category of waves is based on the vorticity equation and the meridional gradient of background absolute vorticity. Upper-level Rossby waves are ubiquitous in mid-latitudes and a key factor in the evolution of most weather systems. In contrast, the physics of diabatic Rossby waves is based upon the generation of potential vorticity due to cloud condensational processes. They can be observed as coherent anomalies of potential vorticity that propagate at low tropospheric levels along intense baroclinic zones, and in some cases they can act as precursors for intense extratropical cyclone development. This rather rare phenomenon has been studied only since about 15 years, and it differs from upper-level Rossby waves in terms of the physical mechanism, the vertical level of its occurrence and its climatological frequency.

Moist processes, especially latent heat fluxes from the ocean surface and convection, are crucial for the formation and development of tropical cyclones. During extratropical transition, the interaction of the tropical cyclone vortex and an extratropical baroclinic zone frequently leads to heavy precipitation and an enhanced vertical mass flux (Davis et al. 2007). The PV modification associated with latent heat release in tropical cyclones undergoing extratropical transition can lead to enhanced anticyclonic flow at or just below the tropopause and thus excite or modify Rossby wave trains (Riemer et al. 2007). Through this diabatic PV modification, extratropical transition systems can have a substantial impact on the midlatitude flow both upstream of an extratropical transition event by slowing the eastward motion of an upper-level trough (Atallah and Bosart 2003) and downstream of the extratropical transition event (Agusti-Panareda et al. 2004; R bcke et al. 2004; Martius 2005). Conversely, the meridional extension of PV streamers and cut-offs into the tropics can initiate the moist convection necessary for tropical cyclogenesis (Davis and Bosart 2003).

2.2c Ensembles and adaptivity

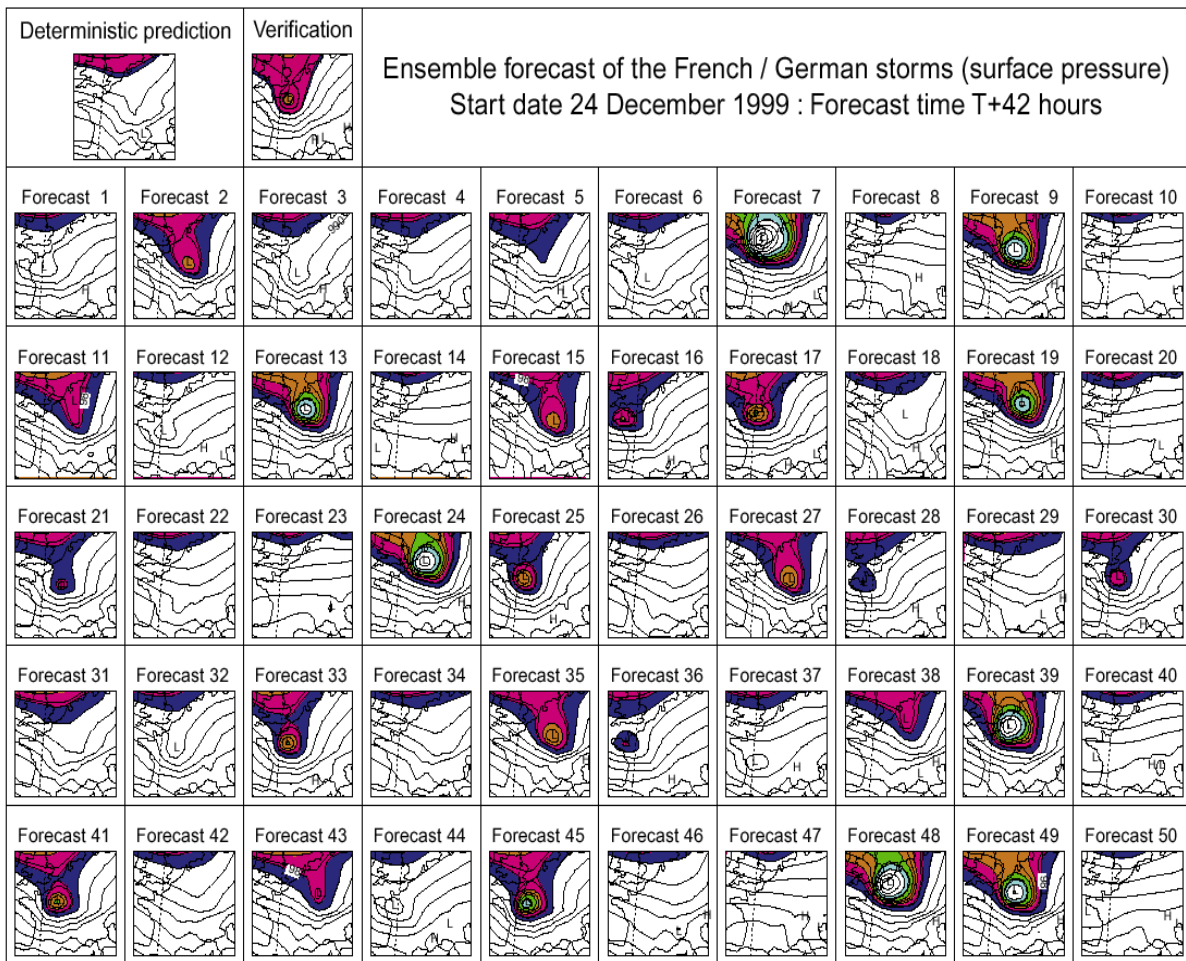


Figure 6: 42-h ECMWF ensemble forecast for Lothar verifying 12 UTC 26 December 1999. Mean sea level pressure (lines and shaded, 4 hPa interval). Taken from THORPEX International Science Plan.

The factors that lead to error growth in numerical weather forecasts can be separated into model uncertainty (related to the inadequate knowledge and/or representation of the relevant physical processes in models) and initial condition uncertainty (related to observational error, inadequate observational coverage, the representiveness of observing systems and the limitations of data assimilation systems). Major improvements in numerical weather prediction can be expected not only through minimising the sources of uncertainty, for example through adaptive observing strategies, but also through an estimation of typical uncertainties for a given high impact weather system, as can be achieved with ensemble prediction systems (EPS).

Adaptive observing strategies, or targeted observations, aim to identify which mix of observations will provide the most skillful forecast. Different techniques can be used to predict the impact of specific observations on the forecast for a particular target area and forecast lead time. Thus so-called *sensitive regions* can be identified, in which it is expected that improvements in the analysis through making additional observations or including more existing observations (e.g. satellite measurements) will lead to an improved forecast. A variety of techniques for sensitive area calculation exist (see references in Sect. 4.2 of Shapiro and Thorpe 2004) all of which involve certain limiting assumptions. These techniques have been used in a number of field campaigns including FASTEX, the Winter Storms Reconnaissance Programme (Szunyogh et al. 2002) and the North Atlantic THORPEX Regional Campaign (NA-TReC) in 2003. Targeted observations are used routinely to improve track prediction of Atlantic hurricanes threatening the USA (Aberson 2003).

Adaptive observations in combination with new instrumentation have the potential to provide significant improvements to the initial conditions of operational forecast models. During the NA-TReC the DLR Falcoln was deployed to obtain targeted observations with doppler wind lidar and dropsondes. The observations were assimilated in the ECMWF global analysis. The wind-lidar measurements represent an areal average whereas the dropsonde measurements give a local value. Due to the higher representivity of the lidar measurements they had approximately 50% larger influence on the analysis and exhibited about 3 times the information content than the dropsonde measurements (Weissmann and Cardinali 2007) (Weissmann et al. 2005).

The effective use of adaptive observing strategies requires research for particular weather systems and forecast ranges in order to determine the appropriate techniques and observations. Current techniques with assumptions of linearity may not be appropriate for medium range forecasts. Future research must consider a variety of techniques including feature based targeting. Such research can be carried out with existing data sets, but will require also new datasets such as will be obtained in future field campaigns (African Monsoon Multidisciplinary Analyses (AMMA) in 2006, THORPEX-Pacific Asian Regional Campaign T-PARC in 2008, HALO-THORPEX and HALO-NEPTUN, THORPEX-North Atlantic Waveguide and Downstream impact Experiment T-NAWDEX).

Uncertainty in a numerical weather forecast can come from imperfect initial conditions (incomplete or poorly assimilated observations), boundary conditions (except in a global model), systematic model errors and unresolved small-scale processes. These uncertainties can be quantified by an ensemble of forecasts that reflects the spread of possibilities consistent with the available data and model accuracy (e.g. Fig. 6). In global medium range ensemble prediction systems the most important source of uncertainty is probably the initial conditions, and a number of methods have been developed to generate perturbations that reflect this uncertainty. (e.g. Toth and Kalnay 1997; Molteni et al. 1996; Buizza 1997). Systematic model errors can be accounted for to a certain extent by including different models in the ensemble, while stochastic parameterisations are being developed to describe the variability of the unresolved scales (Buizza et al. 1999; Craig et al. 2005).

An investigation of the relative contributions of initial value versus model physics perturbations for forecast skill is given in Stensrud et al. (2000), demonstrating that both act primarily on different time scales: model physics variance acts much faster during the first 12 hours than initial conditions. This suggests that for high resolution forecasts of severe weather with limited area models, the initial condition uncertainty is likely to be most important in the global forecast that provides boundary conditions, while small scale variability will be important in the limited area model. The most obvious way to account for boundary condition uncertainty limited area ensemble is to use a set of boundary conditions generated by a global ensemble forecasting system. A brute-force approach that uses every member of the global ensemble is likely to be inefficient, however, since much of the variability in the global ensemble may be confined outside of the domain of the limited-area model. One solution to this problem is to cluster global forecasts that are similar in the target region, and use only a single representative set of boundary conditions for each cluster. This approach has been implemented in the Consortium for Small-scale MOdelling Limited-area Ensemble Prediction System (COSMO-LEPS) developed in Italy (Molteni et al. 2001; Tibaldi et al. 2003) using the COSMO¹ Model of DWD (Steppeler et al. 2003). It was found in this system that most of the variability in the 51 member ECMWF EPS for a region centred on the Alps can be retained by as few as five members. The ability of a stochastic convective parameterisation to provide spread in a mesoscale ensemble forecast has been shown by Bright and Mullen (2002), but little is known about the relative contributions of stochastic perturbations and boundary condition uncertainty to the overall ensemble, other than that it will depend strongly on the meteorological conditions (Done et al. 2006)

The THORPEX Interactive Grand Global Ensemble, TIGGE, is planned as a multi-model, multi-analysis and multi-national ensemble prediction system. TIGGE will integrate user requirements for forecast information, developments in observing systems, targeting, adaptive data assimilation, and model improvements into a multi-model/multi-analysis ensemble prediction system. The initial basic components of TIGGE will be global ensembles

¹ <http://cosmo-model.cscs.ch/public/default.htm>

run to around 14 days, including those run currently at a number of operational centres. These will be collected in near real time and stored in a common format in a number of central data servers for access by researchers in operational centres and the academic communities. This will facilitate research on combination and inter-comparison of different systems; it will become straightforward, for example, to compare the value of multi-model ensembles with those based on perturbations of a single model. The initial TIGGE archive became available for research use during 2007 and will contain ensemble forecasts from at least eight different national and pan-national weather services. The second phase of TIGGE (from 2008, depending on funding) will include additional products and the ability to obtain boundary conditions for ensembles of forecasts from limited-area models. It represents an exciting new opportunity for predictability research at academic institutions.

2.3. Open Questions

The review of prior knowledge presented in the previous section leads to a list of key open questions that will be investigated in PANDOWAE.

2.3a Rossby wave trains: generation, propagation and wave-breaking

- a1)** What are the detailed processes involved in Rossby wave triggering, propagation and amplification?
- a2)** When and how often is the high impact weather, discussed in sect. 2 associated with Rossby wave trains? How do the location, shape and orientation of PV streamers impact the evolution of cyclones and the development of severe weather?
- a3)** How well do operational forecast models represent Rossby wave train generation, propagation, and dispersion? Are there systematic deficiencies in the model or the initial conditions which degrade the simulation of Rossby wave trains?
- a4)** To what aspect of Rossby wave train dynamics is a forecast of severe weather particularly sensitive? Which mechanisms are most important, which are particularly prone to error and why?
- a5)** Is there a quantifiable relation between Rossby wave trains modified by tropical cyclones in the western Atlantic and European high impact weather?
- a6)** What is the interannual variability and seasonal cycle of poleward Rossby wave breaking-events over the North Atlantic-European region as well as their extremes and implications for the large-scale weather pattern?

2.3b Moist processes and diabatic Rossby waves

- b1)** What is the relationship between extratropical cyclone strength and the integrated effect of moist processes? Is this quantifiable for individual weather systems and on a climatological basis?
- b2)** How important are diabatic processes for errors in the initiation, deepening and track of cyclones? Does the importance of diabatic processes differ in various geographical regions?
- b3)** How do moist processes interact with large scale dynamics to alter error growth and predictability?
- b4)** What is the climatological frequency and geographical distribution of diabatic Rossby waves? What are the key parameters that determine their life-time and intensification rate?
- b5)** What is the role of upper-level Rossby waves in the dynamics and predictability of atmospheric phenomena in which moist processes play a fundamental role (lower-tropospheric diabatic Rossby waves, tropical cyclogenesis, Mediterranean cyclones, moist convection)?
- b6)** How well are diabatic Rossby waves predicted with current global forecast models?
- b7)** How do the relative roles of moist processes and dry dynamics differ for Atlantic and Mediterranean cyclones? Do the energy budgets of Mediterranean cyclones with associated high impact weather differ from less severe events?

b8) Can the representation of moist processes be improved by new observing systems? What is the optimal use of additional remote sensing humidity observations in numerical weather prediction (NWP) models?

2.3c Ensembles and adaptivity

c1) Are adaptive observing strategies of value for Atlantic-European weather systems and on what techniques should they be based?

c2) What are the relative roles of large and small scales (as forecast by global and regional models) in limiting the predictability of high-impact weather, especially small scale events such as wind gusts and precipitation?

c3) How can adaptive ensemble forecasting systems be designed to flexibly adjust ensemble size and resolution of ensemble members to best model the uncertainty of the current weather situation?

c4) What role do initial perturbations / stochastic physics / boundary conditions play in limited area ensembles for specific weather events?

c5) What can we learn by using TIGGE data about the dynamics and predictability of the high impact weather discussed in sect. 2?

3. Aims of the Project

The overarching aim of this project is to advance our knowledge and understanding of the processes that determine the predictability of high impact weather in the Atlantic-European sector. Thus we will contribute at a fundamental research level to the development of new strategies for achieving the future forecast capability necessary to mitigate the impact of high impact weather. This aim will be achieved by investigating the development of high impact weather in the context of the synoptic- to planetary-scale framework associated with upper-level Rossby waves, by considering the interaction of moist processes with dynamics, and by exploring the utility of adaptivity and ensemble forecasts. A combination of state-of-the-art numerical models, diagnostic tools and theoretical concepts will be used to address key open research questions in these fields.

Seven individual projects are funded by the DFG. They are located at five different institutions in Germany. The titles and the specific aims of each project over the 6 year time period are as follows.

P1: The impact of extratropical transition on downstream predictability (Prof. Sarah Jones/ Dr. Doris Anwender, Institut für Meteorologie und Klimaforschung, Karlsruhe Institute of Technology (KIT)): To quantify (i) the influence of tropical cyclones undergoing extratropical transition on the development of high impact weather in the midlatitudes and (ii) the role of midlatitude features in initiating tropical cyclogenesis; to investigate the representation of both of these aspects in ensemble forecasts, and to develop diagnostic techniques for analysing ensemble output. The results of this project will be used to develop the concept of a European-led regional campaign. During the first 3 year phase a combination of idealised modelling, analysis of TIGGE data, global ensemble experiments and data impact studies will be applied to extratropical transition cases. This study will contribute to the planning of the THORPEX Pacific Asian Regional Campaign and the analysis of the impact of lidar and dropsonde data from the DLR-Falcon as well as in-situ and remote sensing data from other platforms. The focus here will be on T-PARC cases related to the downstream impact of ET

P2: The dynamics and predictability of Mediterranean cyclones leading to high impact weather (Prof. Christoph Kottmeier/Dr. Ulrich Corsmeier, Institut für Meteorologie und Klimaforschung, Karlsruhe Institute of Technology (KIT)): To investigate the dynamics and predictability of Mediterranean cyclones with particular emphasis on the relative contributions of upper-level forcing, moist processes and surface fluxes to the development of high impact weather, to develop an observational strategy for the HALO-Demo mission NEPTUN, and to contribute to the development of adaptive observing strategies for Mediterranean systems. During the first 3 years cases of Mediterranean cyclones will be investigated using TIGGE data, and high resolution modelling studies will be carried out using the COSMO model.

P3: Role of diabatic processes in the dynamics and predictability of extra-tropical cyclones (Prof. Heini Wernli, Institut für Physik der Atmosphäre, Universität Mainz):

To investigate the role of diabatic processes (latent heat release due to cloud condensation, surface fluxes) for the genesis, intensification and predictability of extratropical cyclones. A particular focus will be on the analysis of diabatically driven cyclones, so-called diabatic Rossby waves. During the first phase we will conduct a climatological evaluation of the link between moist processes and cyclone intensity using reanalysis data and operational and ensemble forecasts and will study diabatic Rossby waves in analysis and forecast data. High-resolution numerical experiments with the COSMO model will serve for an in-depth analysis of the physical processes at play for a selection of case studies. Results from these climatological and model-based studies will contribute essentially to the set-up of the planned European THORPEX experiment T-NAWDEX that will take place during the second phase.

P4: Sensitivity of severe weather over Europe to upstream wave trains and related processes (Prof. Volkmar Wirth/Dr. Hartmuth Borth, Institut für Physik der Atmosphäre, Universität Mainz): To investigate the role of both dynamical and diabatic processes in an operational NWP model regarding the connection between Rossby wave trains and severe European weather, focussing first on selected cases and later on seasonal statistics. During the first phase we will carry out experiments with the global DWD model (GME) for particular case studies to test the sensitivity of severe weather to modifications of the model physics.

P5: Variability and extremes of poleward breaking Rossby waves over the North Atlantic-European region (Priv. Doz. Dr. Dieter Peters, Leibniz Institut für Atmosphärenphysik an der Universität Rostock): To improve our knowledge of the temporal structure of poleward breaking Rossby wave events and of their extremes linked with severe weather, to understand the large-scale influences on poleward Rossby wave breaking and to study the implications of those events for weather. During phase one we will investigate the seasonal cycle and interannual variability of poleward Rossby wave breaking using reanalyses as well as analyses and model Rossby wave breaking for specific zonally asymmetric background flows using a simplified GCM. Related case studies with high impact weather will be simulated with nested mesoscale model MM5 in very high resolution, to investigate the feedback processes between upper tropospheric Rossby wave breaking events and surface severe weather.

P6: Large-scale and local control of severe weather: towards adaptive ensemble forecasting (Dr. George Craig, Meteorologisches Institut, Ludwig-Maximilians-Universität München): To develop the concept of an adaptive ensemble forecasting system that allocates the limited time and computing resources in an optimal way between ensemble members that reflect synoptic-scale uncertainty, those that reflect unresolved small-scale processes, and additional nested models to give very high resolution in the target region. During the first three years an ensemble forecasting system will be developed that encompasses all of these mechanisms, and a series of case studies will be investigated using very large ensembles to identify the key dependencies of this system on meteorological conditions.

P7: Adaptive observing strategies for active airborne remote sensing instruments (Dr. Martin Weissmann, Institut für Physik der Atmosphäre, DLR (German Aerospace Centre)): To develop and evaluate adaptive observing strategies for active remote sensing instruments for future field campaigns and operational applications. In the first three years, adaptive strategies will be tested during T-PARC and their value will be assessed with impact studies that assimilate airborne lidar observations in the ECMWF global model. Furthermore, the sensitivity of high-impact weather predictions to initial condition errors and the value of new observing systems, especially the novel combination of wind and water vapour lidar flown on the DLR Falcon will be investigated.

A collaboration will take place between these DFG funded projects and **Dr. Cornelia Schwierz** of the University of Leeds. The aim of Dr. Schwierz' research is to investigate the predictability of Rossby-wave trains, the processes by which they are triggered and amplified and through which their propagation is modified. She will investigate these Rossby wave properties climatologically using reanalyses, as well as assess their predictability in operational forecast data (e.g. TIGGE). Numerical sensitivity experiments of selected case studies will be conducted to study the role of the components and processes (diabatic

processes, triggers, wave guide) involved with the Rossby wave development leading to high-impact weather events. The outcome will inform PANDOWAE partners and aid in the planning of the European THORPEX experiment T-NAWDEX.

A particular feature of PANDOWAE is that it will contribute to the planning and analysis of a number of observational campaigns. The first of these will be T-PARC proposed for 2008 by the North American and Asian Regional Committees. The priorities of this campaign are to advance knowledge of both extratropical transitions and upper tropospheric wave trains and of their impact on forecast skill. Since the dynamic processes are very similar in the Pacific and Atlantic PANDOWAE research will contribute to the experimental design and the results of this campaign will feed back into the project.

HALO is a new German platform for airborne atmospheric science and Earth observation based on the Gulfstream G550 that will be available for research missions from 2010. The first missions will be demonstration missions provided with a budget of 50 flight hours each. Two of these missions, HALO-NEPTUN and HALO-THORPEX are very relevant for PANDOWAE and the coordinators of the missions are members of the research group. This PANDOWAE research will contribute to the planning of the missions and to the analysis of the data obtained.

HALO-NEPTUN (**coordinator Ulrich Corsmeier**) is an airborne measuring program to provide data for the analysis of the multi scale processes governing the development of Mediterranean cyclones. Measurements using HALO and the Dornier 128 turboprop aircraft will observe the upper tropospheric horizontal wind field, the vertical structure of temperature, humidity and wind as well as the vertical fluxes of latent and sensible heat over sea and land surfaces and the modification of the near surface wind field by the orography. The mission will be coordinated with ground based instruments (surface energy balance, radiosondes, wind- and cloud-lidar).

The HALO-THORPEX mission (**coordinator Andreas Dörnbrack**) will perform HALO flights in order to test adaptive observing strategies to improve the prediction of high impact weather over Europe. Additionally, physical process studies to investigate the three-dimensional water vapour field and dynamical structure of streamers and their relationship to extreme precipitation events are envisaged. The main component of the demo mission HALO-THORPEX will be the simultaneous measurement of the three-dimensional distribution of wind, humidity and temperature with airborne lidar instruments from the lower stratosphere down to the planetary boundary layer including the tropopause region. The HALO targeted observation mission will be planned and performed as part of the international THORPEX research programme.

On the longer time scale PANDOWAE research will shape the development of a European-led THORPEX regional campaign T-NAWDEX. A number of PANDOWAE PIs participated in a European THORPEX workshop at which this experiment was proposed. The research proposed in PANDOWAE would enhance the possibility of realising the T-NAWDEX campaign.

PANDOWAE research will break new ground through:

- Climatologies that link dynamical processes to forecast error;
- Joint case studies based on operational analyses, deterministic forecasts, and TIGGE data using diagnostic techniques such as EOF (empirical orthogonal function) / cluster analyses, piecewise PV inversion, trajectory analyses, and recently developed techniques to identify Rossby wave trains;
- Modelling studies in a real case and idealised framework motivated by these case studies and using limited area and global models for deterministic and ensemble forecasts;
- Data impact studies to demonstrate the utility of new observing systems and to bring dynamical insight into the development of observing strategies for specific weather systems

An exciting new tool that we will exploit in this project is the database of TIGGE. Such a database has not been available previously to the research community. Through the expertise collected in this proposed research group we will be able to develop the methodologies and specific tools to exploit TIGGE data, and to be at the forefront of innovative research with these data.

The focus of PANDOWAE on predictability and dynamical processes means that the aims can be achieved within the discipline of atmospheric science. The transition of basic research to operations and the relation to societal and economic applications will occur within the larger THORPEX programme.

3.1 Summaries of the projects

P1 The impact of extratropical transition on downstream predictability

A poleward moving tropical cyclone that interacts with the midlatitude flow and transforms into an extratropical system – i.e. undergoes extratropical transition (ET) – can cause a severe reduction in the forecast skill for the midlatitude flow downstream. In this project we will investigate the mechanisms that determine this interaction and the associated reduction of predictability. We will apply potential vorticity inversion to analyses, deterministic forecasts, and ensemble forecasts including TIGGE data. We will conduct idealised modelling experiments with the COSMO model and perform high resolution case studies with the COSMO model nested in ensemble members representative of a particular ET scenario. Using an empirical orthogonal function (EOF) and fuzzy cluster analysis we will analyse TIGGE data. Using the ECMWF ensemble prediction system we will carry out experiments to investigate the role of initial perturbations and stochastic physics in ensemble forecasts of ET. Finally, we will conduct data impact experiments to assess the importance of observations related to an ET event for the downstream predictability. This project will contribute to the planning of and analysis of the results from the T-PARC experiment.

P2: The dynamics and predictability of Mediterranean cyclones leading to high impact weather

This project focuses on the dynamics of Mediterranean cyclones and the factors that determine their predictability. A special focal point will be the prognostic identification of cyclones leading to high impact weather in the Mediterranean with storms, heavy precipitation and flash floods especially in the area south of the Alps. Additional criteria to the predicted intensity of the cyclones will be considered, because there are numerous cyclones which are not intense but cause severe weather. We will aim at quantifying the sensitivity of Mediterranean cyclogenesis to large-scale forcing due to an upper-level PV streamer at the dynamical tropopause relative to the impact of moist processes and surface fluxes. The role of embedded convection in the energy and water cycle of cyclones will be investigated in detail by numerical modelling and measurements (funded by other sources) in order to distinguish between cyclones with and without potential for HIW. It is foreseen to concentrate on four typical synoptic scenarios: (i) high amplitude trough approaching the Mediterranean from the west, (ii) remnant circulation in the lower troposphere reactivated by an upper tropospheric trough, (iii) streamer reaching the Mediterranean without cyclogenesis, and (iv) lee-cyclogenesis south of the Alps. With its model studies this project will contribute to future missions of the new German research aircraft HALO and to THORPEX activities coordinated by the European Regional Committee as part of MEDEX. The HALO-project NEPTUN on the “The western Mediterranean as a sensitive region for cyclone formation causing heavy-rain events” has been accepted as a HALO-DEMO-Mission.

P3: Role of diabatic processes in the dynamics and predictability of extra-tropical

Baroclinic instability is the basic mechanism responsible for the growth of extratropical cyclones. Most frequently, tropopause-level disturbances act as cyclogenesis precursors. However, it is known from several case studies that the release of latent heat due to condensation can significantly enhance cyclone growth and alter the structure of storms. In certain cases, it has been hypothesized that diabatically generated, low-level potential vorticity anomalies (so-called diabatic Rossby waves, DRWs) triggered the explosive development. In this project, the role of diabatic processes for extratropical cyclones will be investigated for the first time in a systematic way. Using reanalysis data, diabatic contributions to the intensification of individual cyclones will be quantified in order to obtain a statistical relationship between storm intensification and the along track latent heat release and surface fluxes. Application of the diagnostic to deterministic and ensemble

forecasts will allow quantify the role of diabatic processes for cyclone forecast errors. A refined tracking algorithm will be developed to identify DRW-like cyclones, to build a climatology and assess the predictability of this feature. A selection of cases will be simulated with a high resolution numerical model for gaining a deeper understanding of the physical processes that are involved in the evolution of potentially hazardous cyclones in the North Atlantic / European region.

P4:Sensitivity of severe weather over Europe to upstream wave trains and related processes

Large-scale waves can transport energy and momentum over large distances in the Earth's atmosphere. In particular, it has been shown that large-scale wave trains can trigger severe weather over Europe, suggesting that the causal chain leading to such events can be traced back in time over 1–2 weeks. Yet, the generation, propagation, and association with severe weather of Rossby wave trains are poorly understood. This project aims to investigate the sensitivity of severe weather to different physical processes embedded in upstream wave trains. Main tool will be the global numerical weather prediction model GME of the German Weather Service. A new method will be implemented in order to judiciously modify model physics associated with specific processes. The modifications are meant to represent model deficiencies. The technique will be used in the framework of case studies. It allows one to clearly associate errors to physical processes in the upstream development, and it is complementary to other studies investigating the sensitivity to initial conditions. This research, which addresses one of the key issues from the THORPEX science plan, is considered to be a prerequisite for improving the medium range forecast of severe weather events.

P5:Variability and extremes of poleward breaking Rossby waves over the North Atlantic-European

In the extratropics Rossby waves play an important role in determining the general circulation, especially in the upper troposphere / lower stratosphere region. It is known that events of poleward breaking Rossby waves are often observed over the North Atlantic-European region in wintertime. In this project we investigate the influence of the observed background flow in the upper troposphere on poleward Rossby wave breaking events and the link to severe weather. We will study the seasonal cycle and interannual variability of events of poleward breaking Rossby waves over the North Atlantic-European region and diagnose the extreme cases of the wave breaking events for each season, based on ECMWF Reanalysis (ERA-40) and analyses. The predictability of such events is investigated by using different forecasts data sets. Furthermore, the expected influence of the different zonally varying background flows on poleward Rossby wave breaking will be examined in simplified global ECHAM5 model simulations in order to improve the understanding of this process. A further key investigation is the diagnosis and mesoscale modelling (MM5) for implications of poleward Rossby wave breaking events on the change of the Grosswetterlage (large scale flow) in the lower troposphere, in order to examine different acting mechanisms, and to understand the seasonal differences of the influence and of the impact on severe weather over Northern Europe.

P6:Large-scale and local control of severe weather: towards adaptive ensemble forecasting

High impact weather is often associated with small-scale substructures in larger-scale weather systems. Heavy precipitation or intense wind gusts associated with convection or frontal cyclones will be partially controlled by the synoptic flow, and partly by local orographic features or small-scale dynamical processes. Predictability, or forecast uncertainty, of these events will be influenced by all scales, but in different ways in different meteorological situations. In the first phase of the project, a multi-scale ensemble forecasting system will be developed, that represents the various sources of uncertainty through a hierarchy of models with different resolutions. A key part of this work will be the development of stochastic physical parameterizations for cumulus convection and boundary layer variability, that will allow representation of upscale effects of unresolved variability. In cooperation with other members of the group, case studies of different weather systems will be examined to identify

the primary sources of uncertainty as a function of meteorological situation. Based on this analysis, an adaptive ensemble system can be developed that includes more or fewer members of each resolution and parameterization in order to more optimally sample the uncertainty likely to be present in that environment. Developing and testing the adaptive ensemble will form the second phase of this project.

P7: Adaptive observing strategies for active airborne remote sensing instruments

The first assimilation of airborne Doppler lidar observations in a global weather forecast model recently demonstrated that such observations can significantly reduce analysis and forecast errors. However, the observational data base was limited to eight research flights. Similar impact studies using airborne water vapour lidar data led to forecast deterioration, but the data set was too small to fully explain reasons for the negative impact. In the near future, DLR is planning to deploy an airborne Doppler lidar together with a water vapour lidar during several field campaigns. This is expected to provide a unique data set to investigate the sensitivity of forecast models to initial conditions and to improve the understanding of physical processes causing high-impact weather. This project intends to develop and evaluate adaptive observing strategies for upcoming field campaigns using airborne lidars and will investigate the applicability of an operational adaptation of the observing system to sensitive areas. The collected observations will be assimilated in the ECMWF global model to investigate the value of targeted observations, the potential of air- and spaceborne lidars for the future observing system, and will investigate extra-tropical transition (ET) of tropical cyclones through dedicated sensitivity studies.

4. Tools and Datasets

Following tools and datasets will be used:

COSMO: The Consortium for Small-Scale Modelling (COSMO) model is a non-hydrostatic limited area model based on the Lokal-Modell (LM) (Steppeler et al. 2003) originally developed at the DWD and run operationally at DWD with 7 km horizontal resolution (COSMO-EU, formerly LME) and 2.8 km horizontal resolution (COSMO-DE, formerly LMK). A number of other European weather services have contributed to the development of the COSMO system (<http://cosmo-model.cscs.ch/public/default.htm>). The COSMO model is installed at several partner institutes (Karlsruhe, Mainz, DLR) and has been used for several years with horizontal resolutions ranging from 40 km to 1 km.

COSMO-LEPS: In the COSMO-LEPS system (Molteni et al. 2001; Tibaldi et al. 2003) the COSMO model is nested in 10-15 members of the ECMWF ensemble prediction system (EPS) that are selected using a clustering algorithm.

GME: The GME (Global Model Europe) is the operational global weather forecast model of the German Weather Service (Majewski et al. 2002). It is hydrostatic and based on an icosahedral grid.

ECMWF operational analyses: The current model version T799L91 and the 4d-var data assimilation scheme provide global analyses every 3 hours with a horizontal resolution of approximately 25 km.

ECMWF IFS Deterministic forecasts: The same model version is used for twice daily 10-day global forecasts, started at 00 and 12 UTC.

ECMWF IFS EPS: the operational ECMWF ensemble prediction system is run at a T399L62 with a control forecast and 51 perturbed members. The initial perturbations are calculated using singular vectors (Molteni et al. 1996; Leutbecher et al. 2007) and a stochastic physics scheme is included (Buizza et al. 1999).

ECMWF IFS Data assimilation system: ECMWF currently uses a 12 hour window four-dimensional variational (4D-Var) data assimilation system, where the full model resolution (T799) is used for comparing observation and model equivalents and a reduced resolution (T255/T95) for their minimization. For research applications, the ECMWF system can be applied to reproduce the analysis of any given date with a large number of options:

incorporating additional observations, ignoring particular observation types or observations in particular regions, reducing the resolution and many others changes.

ERA40: and ERAinterim: The ERA40 data set was produced with ECMWF model version T159L60 (corresponding to a horizontal resolution of about 100 km) and the 3d-var data assimilation technique for the time period 1958-2002. It provides a reasonably consistent meteorological data set for this extended period, allowing climatological investigations of various weather phenomena. Currently, a new reanalysis data set is produced, for a shorter time period of about 1980 till today, based upon model version T255L60 and the 4d-var data assimilation technique.

TIGGE: Nine operational Numerical Weather Prediction centres have agreed to deliver a selection of data from global ensemble forecasts in near real time to the THORPEX Interactive Grand Global Ensemble data base. CMA, ECMWF and NCAR have agreed to become Archive and Distribution centres (Bougeault, 2006). TIGGE data will be available for research purposes with a delay of 48 h after the initial time of the forecast.

ECHAM: The GCM ECHAM is a global climate model which was developed at the Max-Planck-Institut für Meteorologie in Hamburg and Universität Hamburg based on the ECMWF forecast model.

MM5: The fifth-generation Pennsylvania State University - National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model. This is a non hydrostatic mesoscale circulation model involving an Arakawa-Lamb B-staggered grid on sigma surfaces.

Piecewise PV inversion: Potential vorticity inversion code (Davis and Emanuel 1991) has been provided by Dr. Christopher Davis and used for previous studies in Karlsruhe and Mainz. This code will be modified so it can be applied to the COSMO model output

EOF/Cluster analysis: This methodology uses a combination of an empirical orthogonal function analysis and a fuzzy clustering applied to the principal components (Harr et al. 2007). Thus ensemble members with similar contributions to the variability patterns are identified through the EOF analysis.

5. Collaboration at National and International Level

There is collaboration with the German Weather Service (Deutscher Wetterdienst, DWD) and with the ECMWF ensuring exchange of knowledge between the specialists responsible for the modelling systems and the PANDOWAE researchers using the models (GME, COSMO, IFS) and conducting experiments with the ECMWF data assimilation system or rerunning ensemble forecasts.

Because PANDOWAE is integrated in the international WMO research programme THORPEX there is also collaboration with the relevant THORPEX partners. On the one hand PANDOWAE will contribute basic research to the THORPEX programme and on the other hand PANDOWAE takes benefit from the collaboration at international level and with operational forecast centres offered by THORPEX.

The knowledge gained in this research group feeds into the planning of observational campaigns. A Pacific Asian Regional Campaign (PARC)² has been proposed for 2008 by the North American and Asian Regional Committees. The priorities of this campaign are to advance knowledge of both extratropical transitions and upper tropospheric wave trains and of their impact on forecast skill. Since the dynamic processes are very similar in the Pacific and Atlantic PANDOWAE research will contribute to the experimental design and the results of this campaign will feed back into the project. The experience gained by Andreas Dörnbrack in the North Atlantic THORPEX Regional Campaign will be of especial value here. Furthermore, the group will contribute to the planning of the HALO-THORPEX and HALO-NEPTUN demo missions and to future THORPEX regional campaigns under the auspices of the European Regional Committee.

Predictability research in PANDOWAE is linked also to a second major international project: AMMA. Research regarding the impact of observations during the AMMA campaign on high impact weather in the Atlantic /Europe and on adaptive observing strategies for the

² <http://www.ucar.edu/na-thorpex/PARC.html>

African and Atlantic region is being coordinated through the activities of AMMA international working group 5 on High Impact Weather Prediction and Predictability.

Additionally, there will be links to different national DFG-Programmes as SPP 1167 (Quantitative Precipitation Forecast, <http://www.meteo.uni-bonn.de/projekte/SPPMeteo/>), SFB 512 (Cyclones and the North Atlantic Climate System), SPP 1726 (Skalenübergreifende Modellierung in der Strömungsmechanik und Meteorologie (MetStröm)), SPP 1294 (Atmosphären- und Erdsystemforschung mit dem Forschungsflugzeug HALO (High Altitude and Long Range Research Aircraft)), SFB 671(Troposphärische Eisphase (Universities of Mainz, Frankfurt and Darmstadt)).

While most of those programmes show only weak links and there is no duplication of ideas, SPP1167 will play a rather important role for PANDOWAE. Although the focus of SPP1167 is mostly on relatively short-range forecasting of precipitation in the warm season in the full range of intensities, it complements well the research proposed in PANDOWAE, which treats the medium-range prediction of the synoptic weather systems that provide the necessary environment for intense precipitation events, as well as other weather hazards. There is an exchange of knowledge and ideas between scientists of the different programmes.

6. References

- Aberson, S. D., 2003: Targeted observations to improve operational tropical cyclone track forecast guidance. *Mon. Wea. Rev.*, **131**, 1613-1628.
- Agusti-Panareda, A., C. D. Thorncroft, G. C. Craig and S. L. Gray, 2004: The extratropical transition of hurricane Irene (1999): a potential-vorticity perspective. *Quart. J. Roy. Meteor. Soc.*, **130**, 1047-74.
- Anwender, D., P. A. Harr and S. C. Jones, 2007: Predictability associated with the downstream impacts of the extratropical transition of tropical cyclones: case studies. Submitted to *Mon. Wea. Rev.* April 2007.
- Appenzeller, C. H., H. C. Davies and W. A. Norton, 1996: Fragmentations of stratospheric intrusions. *J. Geophys. Res.*, **101**, 1435-1456.
- Atallah, E. H. and L. F. Bosart, 2003: Extratropical transition and precipitation distribution: A case study of Hurricane Floyd '99. *Mon. Wea. Rev.*, **131**, 1063-1081.
- Bell, G. I., 1990: Interaction between vortices and waves in simple models of geophysical flow. *Phys. Fluids*, **A 2**, 575 - 586.
- Bougeault, P., 2006: The THORPEX Interactive Grand Global Ensemble (TIGGE): concept and current status. Extended Abstracts, Second THORPEX International Science Symposium, Landshut, Germany, 80-81. WMO TD-1355. (Available from <http://www.pa.op.dlr.de/stiss/proceedings.html>)
- Bright, D. R. and S. L. Mullen, 2002. Short-Range Ensemble Forecasts of Precipitation During the Southwest Monsoon. *Weather and Forecasting*, **17**, 1080 -1100.
- Buizza, R., 1997: Potential forecast skill of ensemble prediction and spread and skill distributions of the ECMWF ensemble prediction system. *Mon. Wea. Rev.*, **125**, 99-119.
- Buizza, R. M., M. Miller and T. Palmer, 1999: Stochastic representation of model uncertainties in the ECMWF ensemble prediction system. *Quart. J. Roy. Meteor. Soc.*, **125**, 2887-2908.
- Burt, S. D. and D. A. Mansfield, 1988: The Great Storm of 15-16 October 1987. *Weather*, **43**, 90-114.
- Buzzi, A., E. Richard and R. Romero, 2005: Summary report on MEDEX studies and scientific results on Mediterranean cyclones causing high impact weather. http://medex.inm.uib.es/documents/Summary_on_MEDEX_studies_Nov05.pdf

- Cardinali, C., R. Buizza, G. Kelly, M. Shapiro and J.-N. Thépaut, 2007: The value of targeted observations. Part III: Influence of different weather regimes. Submitted to *Quart. J. Roy. Meteor. Soc.*
- Craig, G. C., B. G. Cohen and R. S. Plant, 2005: Statistical mechanics and stochastic convective parameterisation. Proceedings of the ECMWF Workshop on Representation of sub-grid processes using stochastic-dynamic models. <http://www.ecmwf.int/publications>.
- Davies, H. C., C. Schär and H. Wernli, 1991 : The palette of fronts and cyclones within a baroclinic wave development. *J. Atmos. Sci.*, **48**, 1666-1689.
- Davis, C. A. and K. A. Emanuel, 1991: Potential vorticity diagnostics of cyclogenesis. *Mon. Wea. Rev.*, **119**, 1929-1953.
- Davis, C. A. and L. F. Bosart, 2003: Baroclinically induced tropical cyclogenesis. *Mon. Wea. Rev.*, **131**, 2730-2747.
- Davis, C. A., S. C. Jones and M. Riemer, 2007: Hurricane vortex dynamics during extratropical transition. *J. Atmos. Sci.* accepted for publication.
- Dirren, S., M. Didone and H.C. Davies, 2003: Diagnosis of “forecast-analysis” differences of a weather prediction system. *Geophys. Res. Lett.*, **Vol. 30**, No. 20, 2060. 10.1029/2003GL017986, 15 October 2003.
- Done, J. M., G. C. Craig, S. L. Gray, P. A. Clark and M. E. B. Gray, 2006: Mesoscale simulations of organised convection: Importance of convective equilibrium. *Quart. J. Roy. Meteor. Soc.*, in press.
- Ebert, E. E., U. Dammrath, W. Wergen and M. E. Baldwin, 2003: The WGNE Assessment of Short-term Quantitative Precipitation Forecasts. *Bull. Amer. Meteorol. Soc.*, **84(4)**, 481– 492.
- Ellrod, G. P. and D. I. Knapp, 1992: An objective clear-air turbulence forecasting technique: Verification and operational use. *Weather and Forecasting*, **7**, 150-165.
- Ertel, H., 1942: Ein neuer hydrodynamischer Wirbelsatz. *Met. Z.*, **59**, 271–281.
- Esler, J. G. and P. H. Haynes, 1999: Baroclinic wave breaking and the internal variability of the tropospheric circulation. *J. Atmos. Sci.*, **56**, 4014-4031.
- Fritsch, J. M. and R. E. Carbone, 2004: Improving Quantitative Precipitation Forecasts in the Warm Season: A USWRP Research and Development Strategy. *Bull. Amer. Meteorol. Soc.*, **85(7)**, 955–965.
- Gabriel, A. and D. Peters, 2006: A diagnostic study of Rossby wave breaking events in the northern hemisphere. *J. Meteor. Soc. Japan.*, submitted.
- Grazzini, F. and G. Van der Grijn, 2002: Central European floods during summer 2002. *ECMWF Newsletter*, **No. 96** – Winter 2002/03, 18-28.
- Harr, P. A., D. Anwender and S. C. Jones, 2006: Predictability associated with extratropical transition of tropical cyclones as defined by operational ensemble prediction systems. *AMS Preprints 27th Conference on Hurricanes and Tropical Meteorology. Monterey, California.*
- Harr, P. A., D. Anwender and S. C. Jones, 2007: Predictability associated with the downstream impacts of the extratropical transition of tropical cyclones: Methodology and a case study of Typhoon Nabi (2005). Submitted to *Mon. Wea. Rev.* April 2007.
- Homar, V., A. Jansa, J. Campins and C. Ramis, 2006: Towards a climatology of sensitivities of Mediterranean high impact weather – first approach, *Advances in Geosciences*, **7**, 259-267.
- Hoskins, B., I. N. James and G. H. White, 1983: The shape, propagation and mean-flow interaction of large-scale weather systems. *J. Atmos. Sci.*, **40**, 1595-1612.
- Hoskins, B. J., M. E. McIntyre and A. W. Robertson, 1985: On the use and significance of isentropic potential vorticity maps. *Quart. J. Roy Meteor. Soc.*, **111**, 877-946.
- Hoskins, B. J. and P. Berrisford, 1988: A potential vorticity perspective of the storm of 15-16 October 1987. *Weather*, **43**, 122-129.
- Jansa, A., A. Genovés, M. A. Picornell, J. Campins, R. Riosalido, and O. Carretero, 2001: Western Mediterranean cyclones and heavy rain, *Meteorol. Appl.*, **8**, 43–56.
- Jones, S. C., P. A. Harr, J. Abraham, L. F. Bosart, P. J. Bowyer, J. L. Evans, D. E. Hanley, B. Hanstrum, R. E. Hart, F. Lalaurette, M. R. Sinclair, R. K. Smith and C. D. Thorncroft, 2003: The extratropical transition of tropical cyclones: forecasting challenges, current understanding and future directions. *Weather and Forecasting*, **18**, 1052-1092.

- Keller, J. L., 1990: Clear-air turbulence as a response to meso- and synoptic-scale dynamic processes. *Mon. Wea. Rev.*, **118**, 986-993.
- Knox, J., 1997: Possible mechanisms of clear-air turbulence in strongly anticyclonic flows. *Monthly Weather Review*, **125**, 1251-1259.
- Kuo, Y.-H., M. A. Shapiro and E. G. Donall, 1991: The interaction between baroclinic and diabatic processes in a numerical simulation of a rapidly intensifying extratropical marine cyclone. *Mon. Wea. Rev.*, **119**, 368-384.
- Lane, T. P., J. D. Doyle, R. Plougonven, M. A. Shapiro and R. D. Sharman, 2004: Observations and numerical simulations of inertia gravity waves and shearing instabilities in the vicinity of a jet stream. *J. Atmos. Sci.*, **61**, 2692-2706.
- Langland, R. H., M. A. Shapiro and R. Gelaro, 2002: Initial condition sensitivity and error growth in forecasts of the 25 January 2000 East Coast snowstorm. *Mon. Wea. Rev.*, **130**, 957-974.
- Leutbecher, M. and T. N. Palmer, 2007: Ensemble forecasting. *J. Comp. Phys. on forecasting weather, climate and extreme events*, submitted.
- Majewski, D., D. Liermann, P. Prohl, B. Ritter, M. Buchhold, T. Hanisch, G. Paul, W. Wergen and J. Baumgardner, 2002: The operational global icosahedral-hexagonal gridpoint model GME: Description and high-resolution tests. *Mon. Wea. Rev.*, **130**, 319-338.
- Magnusdottir, G. and P. H. Haynes, 1996: Wave activity diagnostics applied to baroclinic wave life cycles. *J. Atmos. Sci.*, **53**, 2317-2353.
- Martius, O., 2005: Climatological aspects of wave disturbances on the tropopause and links to extreme weather in Europe. *PhD thesis, ETH Zurich, 2005*.
- Martius, O., C. Schwierz and H. C. Davies, 2006a: A refined Hovmöller diagram. *Tellus A*, **58**, 221-226.
- Martius, O., E. Zenklusen, C. Schwierz and H. C. Davies, 2006b: Episodes of alpine heavy precipitation with an overlying elongated stratospheric intrusion: a climatology. *Int. J. Clim.*, **26**, 1149 - 1164.
- Massacand, A. C., H. Wernli and H. C. Davies, 1998: Heavy precipitation on the Alpine Southside: An upper-level precursor. *Geophys. Res. Lett.*, **25**, 1435-1438.
- Massacand, A. C., H. Wernli and H. C. Davies, 2001: Influence of upstream diabatic heating upon an alpine event of heavy precipitation. *Mon. Wea. Rev.*, **129**, 2822-2828.
- McIntyre, M. E. and T. N. Palmer, 1983: Breaking planetary waves. *Nature*, **305**, 593-600.
- Molteni, F., R. Buizza, T. N. Palmer and T. Petroliagis, 1996: The ECMWF ensemble prediction system: Methodology and validation. *Quart. J. Roy. Meteor. Soc.*, **122**, 73-119.
- Molteni, F., R. Buizza, C. Marsigli, A. Montani, F. Nerozzi and T. Paccagnella, 2001: A strategy for high-resolution ensemble prediction. I: Definition of representative members and global-model experiments. *Quart. J. Roy. Meteor. Soc.*, **127**, 2069-2094.
- Moore, R. W. and M. T. Montgomery, 2004: Reexamining the dynamics of short-scale, diabatic Rossby waves and their role in midlatitude moist cyclogenesis. *J. Atmos. Sci.*, **61**, 754-768.
- Moore, R. W. and M. T. Montgomery, 2005: Analysis of an idealized, three-dimensional diabatic Rossby vortex: A coherent structure of the moist baroclinic atmosphere. *J. Atmos. Sci.*, **62**, 2703-2725.
- Nielsen, N. W. and B. H. Sass, 2003: A numerical, high-resolution study of the life cycle of the severe storm over Denmark on 3 December 1999. *Tellus*, **55A**, 338-351.
- Norton, W. A., 1994: Breaking Rossby waves in a model stratosphere by a vortex-following coordinate system and a technique for advecting material contours. *J. Atmos. Sci.*, **51**, 654-673.
- Parker, D. J. and A. J. Thorpe, 1995: Conditional convective heating in a baroclinic atmosphere: A model of convective frontogenesis. *J. Atmos. Sci.*, **52**, 1699-1711.
- Peters, D. and D. W. Waugh, 1996: Influence of barotropic shear on the poleward advection of upper tropospheric air. *J. Atmos. Sci.*, **53**, 3013-3031.
- Peters, D. and D. W. Waugh, 2003: Rossby wave breaking in the southern hemisphere wintertime upper troposphere. *Mon. Wea. Rev.*, **131**, 2623-2634.
- Petterssen, S. and S. J. Smebye, 1971: On the development of extratropical cyclones. *Quart. J. Roy. Meteor. Soc.*, **97**, 457-482.

- Pielke, Jr. R. A. and R. A. Klein, 2001: Extreme Weather Sourcebook 2001 Edition. *Environmental and Societal Impacts Group, National Center For Atmospheric Research, and the American Meteorological Society, January.* (<http://sciencepolicy.colorado.edu/sourcebook>)
- Pinto, J.G., M. Klawa, U. Ulbrich, R. Rudari and P. Speth, 2001: Extreme precipitation events over northwest Italy and their relationship with tropical-extratropical interactions over the Atlantic. *Proceedings of the 3rd, EGS Plinius Conference on Mediterranean Storms – Baja Sardinia, Italy, October 2001.*
- Pytharoulis, I., G. C. Craig and S. P. Ballard, 2000: The hurricane-like Mediterranean cyclone of January 1995, *Meteorol. Appl.*, **7**, 261-279.
- Postel, G. A. and M. H. Hitchman, 1999: A climatology of Rossby wave breaking along the subtropical tropopause. *J. Atmos. Sci.*, **56**, 359-373.
- Riemer, M., S. C. Jones and C. A. Davis, 2007: The impact of extratropical transition on the downstream flow: an idealised modelling study with a straight jet. *Quart. J. Roy. Meteor. Soc.*, accepted for publication subject to minor revision.
- Röbcke, M., S. C. Jones and D. Majewski, 2004: The extratropical transition of Hurricane Erin (2001): a potential vorticity perspective. *Met. Z.*, **vol.13**, no.6, 511-25.
- Roberts, N. M., 2000: The relationship between water vapour imagery and thunderstorms *JCMM Report No. 110, Joint Centre for Meteorology, University of Reading, Reading, UK.*
- Rossa, A. M., H. Wernli and H. C. Davies, 2000: Growth and decay of an extra-tropical cyclone's PV tower. *Met. Atmos. Phys.*, **73**, 139-156.
- Rossby, C. G., 1940: Planetary flow patterns in the atmosphere. *Quart. J. Roy. Meteor. Soc.* **66**, 68-87.
- Sardeshmukh, P. D. and B. J. Hoskins, 1988: The generation of global rotational flow by steady idealized tropical divergence. *J. Atmos. Sci.*, **45**, 1228-1250.
- Sharman, R., C. Tebaldi, G. Wiener and J. Wolff, 2006: An integrated approach to mid- and upper-level turbulence forecasting. *Weather and Forecasting*, in press.
- Schwierz, C., S. Dirren and H. C. Davies, 2004: Forced waves on a zonally aligned jet stream. *J. Atmos. Sci.*, **61** (1), 73-87.
- Shapiro, M. A. and A. J. Thorpe, 2004: THORPEX International Science Plan. <http://www.wmo.int/thorpex>
- Snyder, C. and R. S. Lindzen, 1991: Quasi-geostrophic wave-CISK in an unbounded baroclinic shear. *J. Atmos. Sci.*, **48**, 76-86.
- Stensrud, D. J., J. W. Bao and T. T. Warner, 2000: Using initial condition and model physics perturbations in short-range ensemble simulations of mesoscale convective systems. *Mon. Wea. Rev.*, **128**, 2077-2107.
- Steppeler, J., G. Doms, U. Schättler, H.W. Bitzer, A. Gassmann, U. Damrath and G. Gregoric: 2003: Meso-Gamma Scale Forecasts Using the Non-hydrostatic Model LM. *Meteorology and Atmospheric Physics*, **82**, 75-90.
- Szunyogh, I., Z. Toth, A. V. Zimin, S. J. Majumdar and A. Persson, 2002: Propagation of the effect of targeted observations: The 2000 Winter Storm Reconnaissance program. *Mon. Wea. Rev.*, **130**, 1144-1165.
- Thorncroft, C. D., B. J. Hoskins and M. E. McIntyre, 1993: Two paradigms of baroclinic-wave life-cycle behaviour. *Quart. J. Roy. Meteor. Sci.*, **119**, 17-55.
- Tibaldi, S., T. Paccagnella, C. Marsigli, A. Montani and F. Nerozzi, 2003: Short-to-medium range limited area ensemble prediction: the LEPS system. *Quaderno Tecnico ARPA-SMR*, **13/2003**.
- Toth, Z. and E. Kalnay, 1997: Ensemble forecasting at NCEP and the breeding method. *Mon. Wea. Rev.*, **125**, 3297-3319.
- Trenberth, K. E., 1991: Storm tracks in the Southern Hemisphere. *J. Atmos. Sci.*, **48**, 2159-2178.
- Uccellini, L. W., 1990: Processes contributing to the rapid development of extratropical cyclones. Pp. 81-105 in: Extratropical cyclones - the Erik Palmén memorial volume. Eds. C. Newton and E. O. Holopainen. *American Meteorological Society.*
- Ulbrich, U., A. H. Fink, M. Klawa and J. G. Pinto, 2001: Three extreme storms over Europe in December 1999. *Weather*, **56**, 70-80.

- Walker, C. C. and G. Magnusdottir, 2003: Nonlinear planetary wave reflection in an atmospheric GCM. *J. Atmos. Sci.*, **60**, 279-286.
- Walser, A., D. Lüthi and C. Schär, 2004: Predictability of precipitation in a cloud-resolving model. *Mon. Wea. Rev.*, **132**, 2, 560-577.
- Waugh, D. W. and L. M. Polvani, 2000: Intrusions into the tropical upper troposphere. *Geophys. Res. Lett.*, **27**, 3857-3860.
- Weissmann, M., R. Busen, A. Dörnbrack, S. Rahm and O. Reitebuch, 2005: Targeted Observations with an airborne wind lidar, *J. Atmos. Ocean. Techn.*, **22**, 1706-1719.
- Weissmann, M. and C. Cardinali, 2007: The impact of airborne Doppler lidar measurements on ECMWF forecasts. *Quart. J. Roy. Meteor. Soc.*, **133**, 107-116.
- Wernli, H. and H. C. Davies, 1997: A Lagrangian-based analysis of extratropical cyclones. I: The method and some applications. *Quart. J. Roy. Meteor. Soc.*, **123**, 467-489.
- Wernli, H., S. Dirren, M. A. Liniger and M. Zillig, 2002: Dynamical aspects of the life-cycle of the winter storm "Lothar" (24-26 December 1999). *Quart. J. Roy. Meteor. Soc.*, **128**, 405-429.
- Wernli H. and M. Sprenger, 2007: Identification and ERA15 climatology of potential vorticity streamers and cut-offs near the extratropical tropopause. *J. Atmos. Sci.*, **64**, 1569-1586.
- Zülicke, Ch. and D. Peters, 2006: Inertia-gravity waves driven by a poleward breaking Rossby wave, *J. Atmos. Sci.*, **63**, 3253-3276.