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Large-Scale Weather Systems: A Future Research Priority

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ABSTRACT

A brief assessment is provided of both the case against and the case for assigning priority to research on large-scale weather systems (LSWS). The three-fold case against is based upon: the emergence of new overarching themes in environmental science; the fresh emphasis upon other sub-disciplines of the atmospheric science; and the mature state of research and prediction of LSWS. The case for is also supported by three arguments. First is the assertion that LSWS research should not merely be an integral but a major component of future research related to both the new overarching themes and the other sub-disciplines. Second recent major developments in LSWS research, as epitomized by the paradigm shifts in the prediction strategy for LSWS and the emergence of the potential vorticity perspective, testify to the theme's on-going vibrancy. Third the field's future development, as exemplified by the new international THORPEX (The Observing System Research and Predictability Experiment) programme, embodies a perceptive dovetailing of intellectually challenging fundamental research with directed application(s) of societal and economic benefit. It is thus inferred that LSWS research, far from being in demise, will feature at the forefront of the new relationship between science and society.

Key words: research priorities, atmospheric dynamics, weather systems, THORPEX

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1. Introduction

The panoply of large-scale weather systems and their finer-scale progeny include cyclones, anticyclones and fronts in the extra-tropics, and easterly waves, tropical cyclones and typhoons/hurricanes in the subtropics. The irregular occurrence of these systems establishes to a large measure our day-to-day weather, and impacts upon both our personal lives and economic activity. Moreover the irregularity points to the underlying transient and chaotic character of the systems, and to the desirability of their accurate prediction. One repercussion has been that the study and prediction of these systems has propelled developments in and long been been the centerpiece of the atmospheric sciences. In essence consideration of the field's future status relates to the development or demise of the historical core field of the atmospheric sciences.

In this overview we first set out the case against large-scale weather systems (LSWS) remaining a major research priority (section 2). These arguments are first countered by reexamining the case against (sections 3 and 4). Thereafter an outline provided of reasonable expectations for the field's future development (section 5), and a rationale set out for according priority to LSWS research (section 6).

2. The case against

In this section three generic arguments are advanced in support of downgrading the status of research on large-scale weather systems (LSWS).

2.1 *Emergence of new and significant environmental challenges*

It has been long argued (Wiscombe and Ramanathan, 1985) that, although there remains scope for good and useful research to be undertaken on the dynamics and forecasting of large-scale weather systems, from the 1970s onwards the focus and excitement in the atmospheric sciences has been shifting toward other arenas. These arenas have come to include climate change and the impact of greenhouse gases, stratospheric ozone depletion, and tropospheric pollution.

A distinctive feature of these arenas is that their emergence has been paralleled by a growing and widespread concern for the state of the environment. This concern has also prompted political activity at

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the international level and resulted in a raft of frameworks, protocols and conventions. Example include the "Convention on Long-range Transport of Air Pollutants" of 1979, the "Vienna Convention on the Protection of the Ozone Layer" of 1985, the "Montreal Protocol" of 1987, the "United Nations Framework for Climate Change (UNFCC)" of 1992, and the "Kyoto Protocol to the UNFCC" of 1997. These para-legislative documents have on the one hand been accompanied and in part undergirded by directed-research in the respective arenas (e.g. the longstanding and continuing activity of the "International Panel for Climate Change"), and on the other helped propel research on the overarching theme of the well-being and fragility of earth-atmosphere system.

2.2 *Emphasis on scientific challenges in other sub-fields*

The second argument is based upon noting that, in parallel to and prompted in part by the emergence of the fore-mentiond new arenas, there has also been a heightened recognition of the importance of and a resurgence of interest in the scientific challenges linked to other sub-fields of the atmospheric science. An exemplary list of these (re)envigorated sub-fields includes:- atmospheric composition and chemistry, radiative transfer, cloud and aerosol physics, meso-scale weather systems, air-sea interaction and land-surface processes.

In particular it has been argued (Wiscombe and Ramanathan, 1985) that there is a need to portray a broader profile for the atmospheric science that both encompasses these sub-fields and reflects a better balance between them. The desirability of a broadened perspective has been further heightened by the growing appreciation that at the heart of climate research is the inter-connections between the various sub-fields (Dickinson, 1983).

In this new paradigm the subject of large-scale atmospheric dynamics and prediction would take its place as one of the sub-fields, albeit a sub-field viewed as being somewhat removed from the discipline's mainstream of activity and excitement. In the same vein it could further be argued that the upsurge in the study of meso-scale systems is the natural continuation and extension of LSWS research but applied to a smaller spatial-scale. The caveat here is that such a statement again amounts to a de-emphasizing of research on large-scale weather systems.

2.3 *Alleged end-game for weather prediction*

The third and seemingly most trenchant argument relates directly to the core business of LSWS studies, namely the provision and improvement of reliable weather forecasts. This core activity has a long history and been the subject of extended attention. It has been argued that mid-latitude weather prediction out to one week has become a relatively mature research area. Moreover it was inferred two decades ago (Wiscombe and Dickinson, 1985) that it attained its zenith.

More recently, and far more caustically, it has been stated ("NWS 2025" published in 1999) that by the year 2025:

· the data problem for weather prediction will be essentially solved,

· observational errors as known today will have been eliminated,

· global weather prediction with 1 km resolution will have reached the theoretical limits of predictability theory,

· numerical prediction in the 0–2 day time frame will be essentially perfect.

These assertions carry with them the implication that weather prediction, as practiced in the late-1990s, has entered its end-game phase.

Furthermore proponents of these assertions indicate that the key to realizing the fore-mentioned goals will be increased computer power, improved observations, and improved understanding of the parameterized sub-grid scale processes. A corollary of these assertions is that the agenda can be achieved without further understanding of the dynamics of LSWS (other than the embroidery effect of very small-scale sub-grid scale processes). In effect acceptance of the above set of assertions would not only herald the imminent demise of conventional weather prediction, but also immediately exclude a significant role for the fundamental studies of LSWS.

3. The case for: Linkages

Taken together the three arguments set out in the previous section appear to constitute a powerful case against assigning significant priority in the future to the study of large-scale weather systems. In this section we revisit and respond to these arguments by examining more closely the nature of the links of LSWS to both the emerging research arenas and to the (re)invigorated sub-fields.

It is accepted that LSWS are integral to the emerging arenas and sub-fields. Here we seek to demonstrate that, over and beyond this overt linkage, specific aspects of LSWS are highly significant to the new challenges, and that consideration of these aspects is central to the future development of the new arenas.

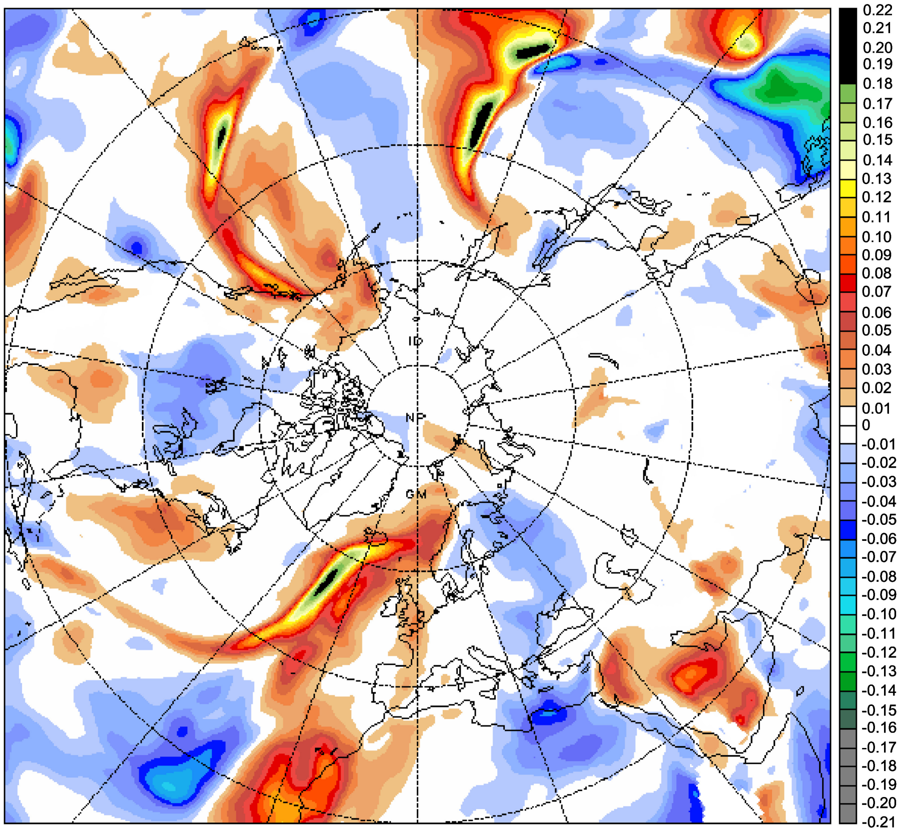

Fig. 1. Depiction of the instantaneous poleward transport of specific humidity on the 850 hPa surface as derived from the ECMWF ERA-40 data set for 0000 UTC 10 January 2002. The displayed scale for the poleward flux of specific humidity is linear and covers the range $+/-22.0\,10^{-2}$ $\mathrm{m\,s^{-1}}$. Note the narrow elongated bands of positive transport in the Atlantic and Pacific related to warm conveyor belts aligned parallel to contiguous surface fronts.

3.1 *Links to the new arenas*

3.1.1 *Climate research*

In relation to climate, LSWS play a major role in establishing the overall latitudinal and vertical thermal distribution. More particularly it is the rich coherent sub-structures of LSWS's extra-tropical cyclones and anticyclones (narrow tropopause-level jet streams, tight surface fronts, banded conveyor belts extending from the low-troposphere to the upper-troposphere, and elongated stratospheric filaments extending deep into the troposphere) that accomplish much if not most of the redistribution. Figure 1 provides one example of the spatial scale, instantaneous distribution and local nature of one genre of these sub-structures. The figure displays the instantaneous distribution of the poleward flux of specific humidity at a low-tropospheric level, and it is evident that much of the flux takes place within distinctive, specially-separate, narrow bands (these so-called warm conveyor belts ahead of surface cold fronts).

The existence of the forementioned sub-structures has, or should have, a bearing upon the design of climate models. These fine-scaled sub-structures are at the limit of the resolution of many current global numerical weather prediction models, and are at best very poorly (if at all) represented in the current genre of global climate models. More pointedly the major contribution of these features to the global momentum, sensible and latent heat fluxes is neither adequately represented nor explicitly parameterized in climate models, and contribution to these fluxes can only be made by planetary-scale waves, the resolved synoptic-scale waves and the imposed horizontal diffusion. Amelioration of this situation requires either explicit representation using higher spatial resolution or explicit parameterization of the influence of the sub-structures within baroclinic eddies. The first option carries a high computational penalty, and the second option requires the development of a refined parame-

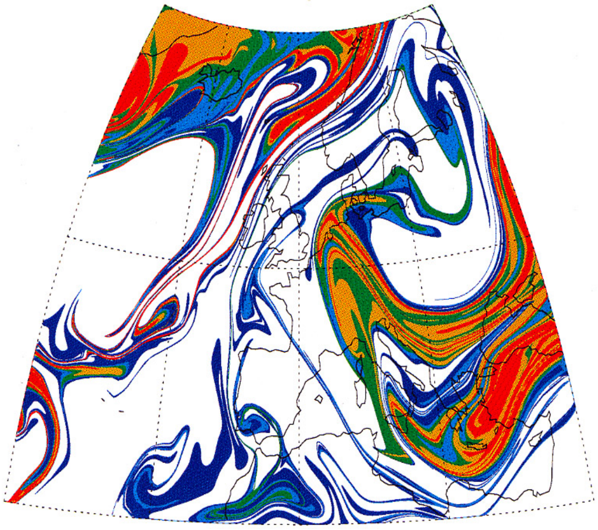

Fig. 2. Depictions of the PV distribution (shading in pvu=10^{-6} K kg^{-1} m^2 s^{-1}) on the 315 K isentropic surface at 0000 UTC on the 11 December 1991). Representation derived from multi-day forward contour integration of the wind fields of the ECMWF analysis. Note the extremely fine-grained structures associated with Rossby wave-breaking at the downstream end of the Atlantic storm track.

terization scheme beyond that currently available. Thus future strategies for the development of comprehensive and/or intermediate complexity climate models will have to grapple with the relative merit of representing the effect of LSWS sub-structures as opposed to incorporating additional physical and biogeochemical processes (c.f. Held, 2005)

In relation to intra-seasonal and inter-annual patterns of climate variations (PCV) comparatively little is known or understood of their link to LSWS. However there are hints to the existence and nature of the linkage. For example it has been suggested (Shapiro et al., 2000) that there is a "PCV⟶LSWS" link such that the two phases of the El-Nino establish an ambient flow field to their north that favours anticyclonic (LC2) development during El Niño and cyclonic (LC3) development during La Nina (c.f. the dynamical categorization of baroclinic flow evolution in Davies et al. (1991), Thorncroft et al. (1993)]. Likewise an "LSWS⟶PCV" link or at least a two-way "LSWS⟷PCV" interconnection is clearly conceivable since a suitably located and large amplitude quasi-stationary LSWS of sufficient spatial scale and duration (e.g. a blocking event) could in principle exert a significant influence upon, say, the monthly value of the index for an inter-annual pattern of climate variation (such as the NAO or PNA). Such a linkage is supported by comparing time series of blocking frequency in the Atlantic and Pacific with the respective time series for the negative phases of the NAO and PNA (see e.g. Croci-Maspoli, 2005). Indeed the strength of the correlation suggests a strong relationship between this particular weather phenomenon and the two leading patterns of extra-tropical climate variability.

In relation to climate change itself any net change will to a large measure be manifested locally through the change in amplitude, frequency and location of LSWS. This in turn underlines the need to identify the sensitivity of LSWS to change in the background fields, and thereby underpins the case for understanding the dynamics of LSWS and the nature of their linkage to the large-scale flow.

3.1.2 *Link to atmospheric composition and global pollution transport*

LSWS also play a major role in establishing the spatial distribution of the atmosphere's chemical constituents. Their contribution involves troposphere-spanning and hemisphere-encircling flow features as well as highly localized coherent flow features. It is these features that accomplish much of the global transport and perform the scale-collapsing stirring of the chemical constituent distribution that ultimately makes molecular diffusion more effective.

The sub-structures of LSWS referred to in the previous sub-section are an integral part of the transport and stirring. To illustrate this point Fig. 2 shows a sequence of charts depicting the potential vorticity (PV) distribution on a tropopause-transecting isentropic surface. The displayed fine spatial-scale shows an interlacing of (high PV) stratospheric air and (low PV) tropospheric air that is characteristic of stirring and the prelude to stratosphere-troposphere exchange and mixing. The import of the pattern is underlined by noting that (a) the displayed pattern can also be viewed as a crude proxy for ozone abundance or moisture deficit, and (b) the pattern's spatial-scale is at the limit of that resolvable in current Numerical Weather Prediction (NWP) models and neither adequately represented nor explicitly parameterized in current global chemistry models. Inferences are that the sub-structures of LSWS can (and do) contribute to the distribution of the atmosphere's constituents, their effect is both salient and subtle and is currently substantially overlooked, and that the accompanying dynamics is intricate and only partially understood.

The sub-structures also pose significant challenges in the rapidly developing field of the short-range forecasting of pollutant transport. To illustrate this point Fig. 3 shows, as a function of latitude-longitude, the posteriori "relative dispersion" of macro fluid parcels advected by the flow. Seminal features include the band of low dispersion aligned along the axis of the

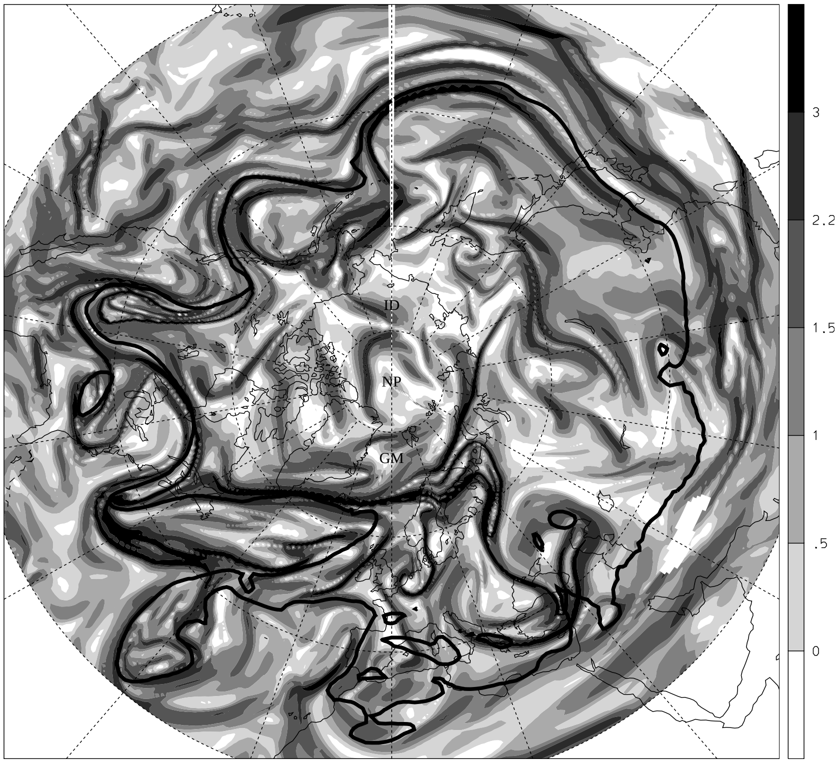

Fig. 3. Relative dispersion (σ) over a 48 hour time period of macro air-parcels on the 320 K isentropic surface with σ displayed as a function of initial parcel centroid. The black contour denotes the 2 pvu isoline and is a proxy for the location of the jet. Note the banded structure aligned along the "jet".

extra-tropical jet with two accompanying bands of extremely high disper sion aligned astride the jet. It follows that prediction of pollutant transport and dispersion in such a setting requires accurate specification of the strength, structure and location of the jet, and yet these are characteristics that are frequently mis-analyzed (and presumably mis-forecasted) in current NWP assimilation and prediction suites. Other highly sensitive locations for predicting pollutant distribution are regions of flow bifurcation. In essence the large-scale stirring of chemical species by atmospheric flow is highly chaotic when viewed in a Lagrangian framework, and future research on pollutant dispersion will have to grapple with this particular issue.

Allied to these pollutant transport studies is the evolving research focus on establishing the four-dimensional distribution of key atmospheric constituents (e.g., sulphur dioxide, aerosols and particulate matter, nitrogen dioxide, carbon monoxide and dioxide, ozone, methane, and nitrous oxide) for monitoring and regulatory purposes. The data assimilation suites of global numerical prediction systems offer an effective way of ingesting and blending the mix of satellite and in-situ constituent measurements to provide the required dynamically consistent distributions. An addendum to this development is that it will open up entirely new vistas for the atmospheric chemists since it will enable them to view the evolution of the global atmosphere's chemical distribution in real time. This has the makings of a scientific revolution, and it will have been enabled by the sophisticated tools developed and currently being further refined for the prediction of LSWS. In turn information from the derived fields concerning the location and rates of change could help spur the further study of LSWS.

3.2 *Links to the other sub-fields*

Here we comment briefly on the linkage of LSWS research to other sub-fields of atmospheric science. The latter include aerosol and cloud physics, mesoscale weather systems, planetary boundary layer, air-sea interaction and air-land processes (aspects of the linkage with atmospheric chemistry were already considered in the previous sub-section), and each sub-field has its own distinguished history.

The argument advanced in section 2.2 was that these sub-fields deserved to be given more prominence. It is not the purpose here to gainsay this point, but rather to note that (a) there is significant scope for research and development at the thematic interface of these fields with that of LSWS, and (b) research at the interface with LSWS constitutes arguably the most scientifically challenging and most practically relevant development in these other sub-fields.

Point (a) is linked to generic aspects that relate LSWS to the other sub-fields. There is a strong measure of inter-dependence such that LSWS form the ambient environment for, interact with, and mediate the influence of the processes and flow features associated with the other sub-fields. The scope for research on the interdependence can be illustrated with two examples. First significant vertical transport of air (and aerosols) out of the boundary layer and high into the overlying atmosphere often occurs when a large-scale weather system radically disturbs the boundary layer, plays a role in instigating and sustaining a tropopause-spanning mesoscale cloud system, and rapidly transports the resulting air (with its enhanced aerosol and moisture content) away from the source region at much higher tropopause elevations, and finally the enhanced aerosol and humidity distribution downstream can play a sensitive role in the regions in-situ radiative transfer. Second the so-called Madden-Julian Oscillation can be viewed as a synergetic interaction between the boundary layer, individual clouds, meso-scale cloud ensembles and the large-scale weather system itself.

Point (b) is based on the premise that LSWS systems constitute not only the ambient environment that influences the occurrence, spatial extent, amplitude and duration of the processes and phenomena associate with the other sub-fields, but also that the ultimate impact of the latter processes and phenomena upon the global circulation and climate are mediated via the bridge formed by LSWS.

The linkages noted earlier in section 3.1 and again above serve to underline that future development in the emerging arenas and the other sub-fields of the atmospheric science could and should be influenced by the existence and the influence of LSWS. This can be viewed as a part of the desired integration of atmospheric science sub-fields, and provides a raison d'etre for continuing LSWS research as a part of the entire enterprise. In contrast in the next two sections we set out the case for a continued focus on LSWS research based upon the subject's own distinctive character.

4. The case for: Current status

In this section we revisit the issue raised in section 2.3 regarding the implications of the mature status of LSWS research upon its future viability, and we preface our consideration with two linked remarks. First NWP is the applied component of LSWS research, and hence both its underpinning and development depends upon advances in the theoretical understanding of the basic dynamics of LSWS. In effect the field's future health is not primarily a function of its level of maturity or the attainment of a pre-assigned set of goals (c.f. section 2.3), but rather by its vitality. Second basic research is an evolving process that is inherently difficult to predict, and current trends are one of the few meaningful indicators.

Here we assess the current status of LSWS research by asking whether it constitutes a strikingly vibrant research field. To be accorded such an accolade a field should embody new and fundamental developments that amount to a paradigm shift in the nature and perspective of the research. It is our contention that LSWS research, far from being moribund field facing imminent demise (c.f. section 2.3), deserves such an accolade. The case is set out below.

4.1 *Revolution in LSWS prediction*

There has been a sea change in the nature of LSWS weather prediction over the last two decades. This can be highlighted by noting the change of the field's approach to the concept of "conformity to observations" (Davies, 2005).

From 1850 onwards there has been a demand for more and better quality observations to improve the specification of the initial atmospheric state for the subsequent forecast. From the 1920s onwards there has been a determined attempt for predictions to better match the contemporaneous observations.

In stark contrast in recent times practitioners, whilst still acknowledging these two desiderata, have pursued different strategies. First the criterion of conformity of the initial atmospheric state to observations has been relaxed and replaced in the data assimilation process by the search for a four-dimensional flow evolution that is closest to that approximated by the observations. Second the criterion of the conformity of the prediction to the subsequent observations has been forsaken and replaced in the ensemble prediction approach (e.g. Molteni et al., 1996) by a search for a set of flow evolutions that differ "minimally" from one another in terms of their initial state and "maximally" from one another in terms of their subsequent evolution. This approach, designed to assess the predictability of the specified initial state, equates to generating a multitude of maximally incorrect forecasts! This is a true paradigm shift.

These developments have been under-girded by subtle physical considerations of the precise nature of atmospheric flow (sic. state of balance beyond simple quasi-geostrophy) and by the application of elegant physical concepts and mathematically advanced techniques (e.g., four-dimensional variational principles for data assimilation, and singular vector perturbations for ensemble forecasting) that deliver practically relevant information. They serve not only to rebut the suggestion that weather prediction has entered its end-game phase, but they open up a new panorama for an integrated form of weather prediction that will entail real time linkages between: formulating the nature and space-time density of observations required to specify the initial fields; determining the nature and number of the necessary deterministic forecasts; and tailoring the production and nature of forecasts to the specific and individual needs of diverse recipients.

Finally it is also salutary to note that the understanding and forecasting of LSWS amounts to the prediction of the evolution of a highly non-linear, complex, and chaotic system. The challenge is enormous, and recent advances support the claim that weather prediction is a highly successful scientific enterprise that is pioneering the approach to the study of such systems.

4.2 *A paradigm shift in the perception of LSWS*

The last two decades has seen the emergence of a fundamentally new "potential vorticity perspective" for studying the dynamics of large-scale atmospheric flow (Hoskins et al., 1985). The potential vorticity (PV) perspective is founded on a triplet of concepts: the Lagrangian quasi-conservation of a fluid parcel's PV; the existence of an inversion relationship for balanced flow that links the PV distribution to the wind and thermal fields; and the partitioning of the overall PV distribution into seminal sub-elements enabling the attribution of the flow at a given point to the separate contribution of the sub-elements.

The perspective provides a physically insightful and mathematically elegant approach to analyze and interpret the dynamics of the flow, and it has (and is) exerting a major influence upon our perception of the nature of LSWS and upon developments in the field. This can be highlighted by noting that it is providing:

· a new way to conceptually sub-divide the atmosphere by viewing it as comprising an over-, middle- and under-world, and with particular note also being taken of the tropopause's topography (Hoskins, 1991),

· a new way to identify and characterize individual flow phenomena, e.g., an atmospheric block can be viewed as local negative anomaly in the upper-tropospheric PV distribution (see e.g., Pelly and Hoskins, 2003; Schweirz et al., 2004b), whilst a mature cyclone can be viewed as a vertically coherent PV tower (Fig. 4),

· fresh insight on some basic flow features, e.g. atmospheric Rossby waves are viewed as propagating on the intense and localized isentropic PV gradient associated with the jet stream (see e.g., Schweirz et al., 2004a),

· a new framework for interpreting flow development including baroclinic and barotropic instability (Hoskins et al., 1985), classes of cyclogenesis (Appenzeller and Davies, 1996), the role of diabatic heating in cyclogenesis and the modification of the upper- troposphere's PV distribution (see e.g., Rossa et al., 2000), and

· prompting new questions, e.g., identification of localized positive PV anomalies in the extratropical middle-world as cyclogenesis precursors prompts the question of the origin of the precursors.

In addition the PV perspective is proving useful for numerical weather prediction, and examples include the analysis of forecast errors (e.g., Demitras and Thorpe, 1999; and Dirren et al., 2003), and the interpretation of the rapid growth associated with highly structured singular vectors (Badger and Hoskins, 2001). Likewise it provides insight on a range of other phenomena and processes such as stratosphere-troposphere exchange (Holton et al., 1995), sudden stratospheric warmings (Davies, 1981), the assessment of the robustness and quasi-impermeability of the polar vortex (Mo et al., 1998), and the dynamics of some meso-scale systems. It is also being adopted for the study of balanced flow in other geo- and planetary atmosphere- flow systems.

In short the foregoing indicates that the PV perspective of LSWS bears the hallmarks of a paradigm shift that is transforming the accepted framework for atmospheric dynamics. This is the very essence of a vibrant research field.

5. Expectations and THORPEX

Future development of LSWS research is constrained by the nature of the challenges. From a purely dynamical standpoint the challenge is to develop effective methods for understanding the complex, chaotic nature of large-scale flow. From a prediction standpoint the challenge is to construct computationally efficient and operationally feasible numerical models capable of resolving and representing atmospheric flow, allied to the massive task of acquiring adequate global observational data and assimilating that data into models in a dynamically consistent fashion.

It would ordinarily be difficult to make strong statements regarding the future of the field. However a ten-year international research programme (THORPEX) has recently been established (Shapiro and

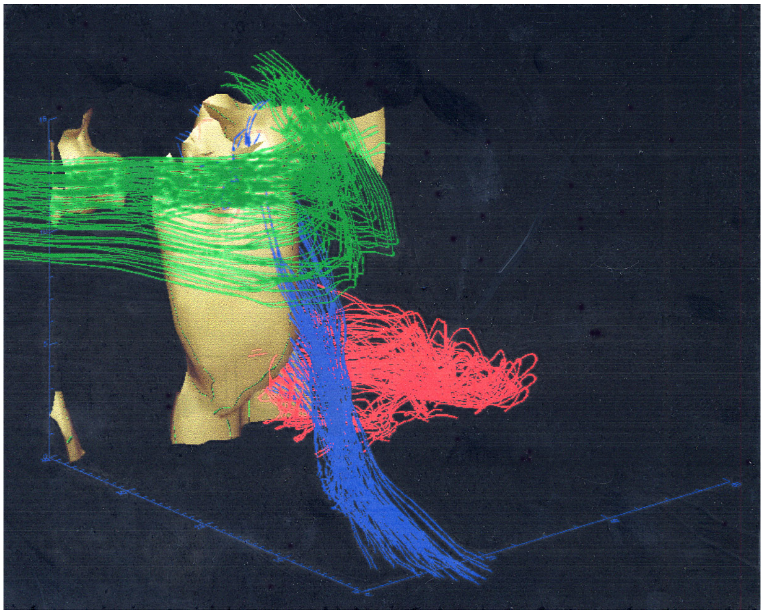

Fig. 4. Depiction of a cyclone's PV tower together with a selection of backward trajectories of air from the tower. Note that the tower is fed by three airstreams of high PV values—one descending adiabatically from the stratosphere and two ascending diabatically within airstreams associated with surface frontal zones (Rossa et al., 2000).

Thorpe, 2004; Rodgers et al., 2005). THORPEX stands for "The Observing System Research and Predictability Experiment" and it is designed specifically to build upon the current and foreseen capabilities of LSWS research. It serves as a focus for future activity in the field, helps identify the major challenges, and provides an organizational framework that bridges the realms of fundamental research, operational forecasting, and the forecast application.

It is geared to making advances across a broad front including extending the range of skilful weather forecasts to time-scales of value in decision-making using ensemble forecast techniques; developing accurate and timely weather warnings designed ab initio to be user-useful, and contributing to mitigating the effects of weather-related natural hazards. The research will encompass activities related to: predictability and dynamical processes; observing systems; data assimilation and observing strategies; and societal and economic applications, and it will seek to deliver significant and quantifiable improvements in forecast-related decision making skill with an attendant measurable reduction in societal distress, and developing improved global and regional forecasting systems linking developed, developing and least developing nations (Rodgers et al., 2005). Clearly the goals and activities of THORPEX are closely aligned to the challenges currently confronting LSWS research. THORPEX will provide a spur to and help guide LSWS research, and the latter will be the basis for achieving the transparently worthwhile goals of the THORPEX.

Within THORPEX itself basic fundamental research on LSWS is aligned closely to its sub-component entitled "Predictability and Processes". The scope for this sub-component (Szunyogh and Wernli, personal correspondence) is both challenging and wide-ranging. It includes consideration of the role of Rossby wave dynamics in predictability; impact of moist processes upon extratropical development and predictability; large-scale response of the atmosphere to organized tropical convection; predictability of tropical cyclones; tropical-extratropical interaction, extratropical transition and downstream development; dynamics of ensemble prediction; prediction on sub-seasonal time scales and blocking; and idealized and low-dimensional model experiments.

These fundamental research themes extend beyond the confines of pressing prediction-orientated research to encompass most of the currently perceived challenges in atmospheric dynamics.

6. Further remarks

The issue of assigning priority to any particular research field is clearly a complex mix of perceived scientific, technological, social, economic and political factors. In the present study the arguments commonly advanced against assigning priority to this research field have been countered directly by demonstrating that LSWS research needs to and will be an important and integral component of future research on climate and atmospheric composition, by illustrating the current vibrancy of the field, and by pointing to the development of an international research programme (THORPEX) that is geared to run for the next decade and that builds specifically upon and will require the further development of LSWS research.

It is noteworthy that THOPRPEX embodies a dovetailing of highly challenging fundamental research with directed application(s) to provide achievable societal and economic benefits. Thus on the one hand the fundamental research challenges (- see list at the end of the previous section) are intellectually stimulating and scientifically demanding, and address the observational, theoretical and numerical modelling of a highly non-linear, complex and chaotic system. In effect this is cutting-edge research at the frontier of a nascent and rapidly evolving field of science. On the other hand the effects of LSWS-linked events continue to contribute significantly to the loss of life and the exponentially escalating insured loss from natural catastrophes. For example in 2005 the latter amounted to a historical record of circa. 80 billion US dollars. This combination of quality basic research allied to social and economic relevance is central to the emerging relationship between science and society, and THORPEX and LSWS research is an exemplar of the new relationship.

Finally note that the foregoing remarks are subject to the inevitable limitations that accompany any forecast, and that the evolving nature of the research enterprise itself is such that "in the distance tower still higher (scientific) peaks which will yield to those who ascend them still wider prospects" (a quote accredited to J. J. Thomson).

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