What’s so hard about making a theory of atmospheric blocking?

Noboru Nakamura
University of Chicago

THE UNIVERSITY OF
CHICAGO

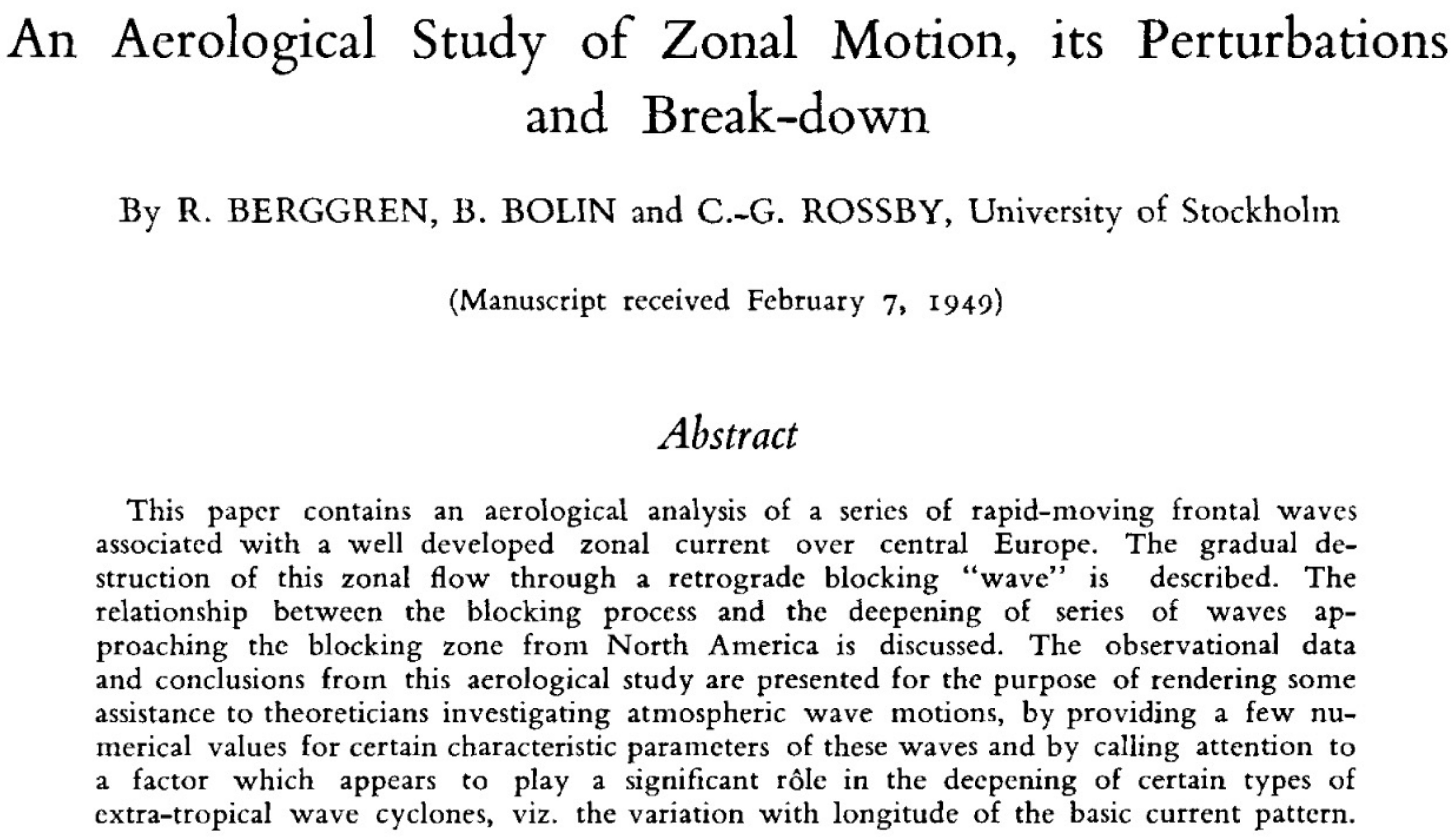
US CLIVAR

NOAA

NSF

Workshop on Blocking & Extreme Weather in a Changing Climate 3/18/2024

Blocking has been known for over 7 decades



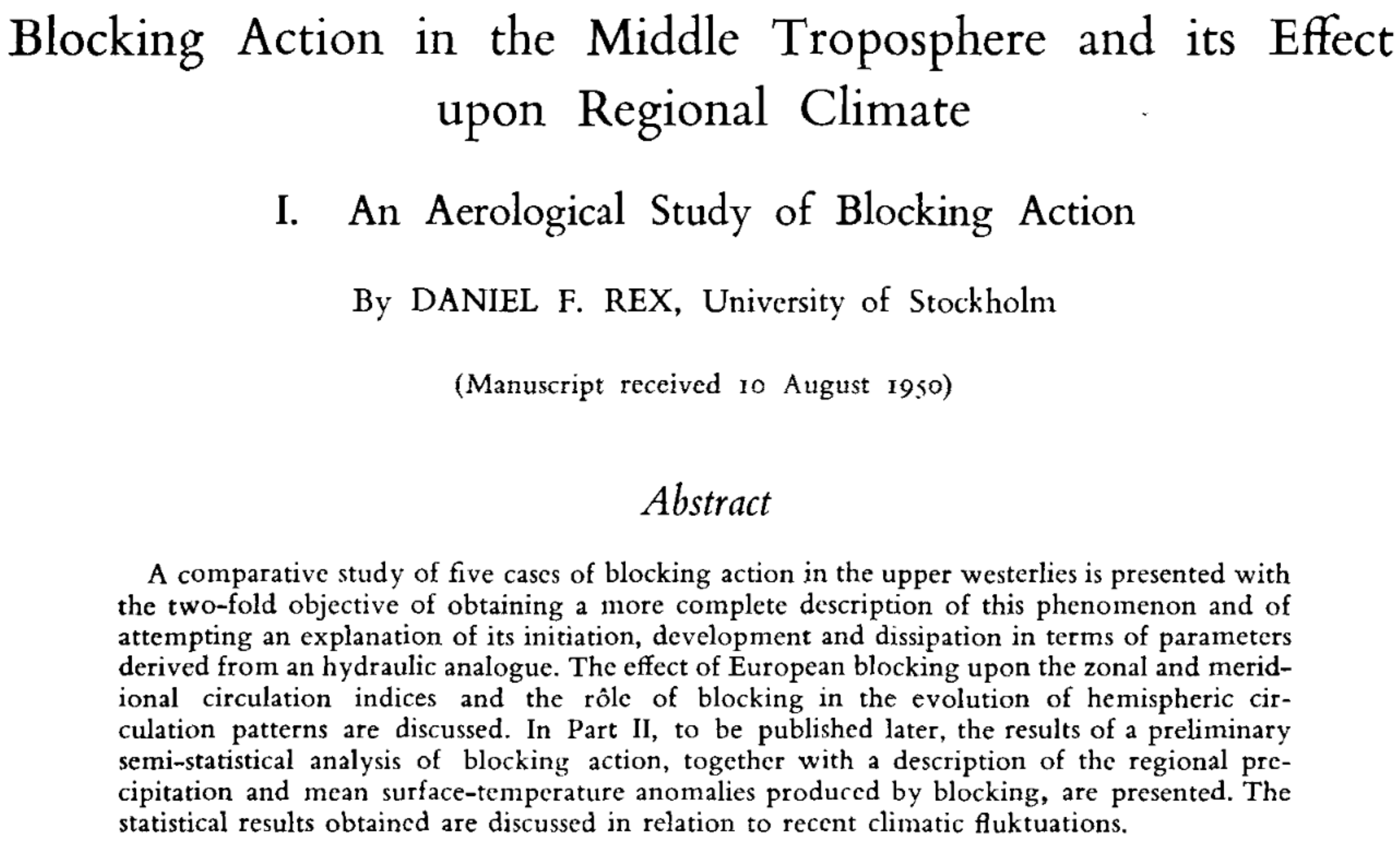
An Aerological Study of Zonal Motion, its Perturbations and Break-down

By R. BERGGREN, B. BOLIN and C.-G. ROSSBY, University of Stockholm

(Manuscript received February 7, 1949)

Abstract

This paper contains an aerological analysis of a series of rapid-moving frontal waves associated with a well developed zonal current over central Europe. The gradual destruction of this zonal flow through a retrograde blocking "wave" is described. The relationship between the blocking process and the deepening of series of waves approaching the blocking zone from North America is discussed. The observational data and conclusions from this aerological study are presented for the purpose of rendering some assistance to theoreticians investigating atmospheric wave motions, by providing a few numerical values for certain characteristic parameters of these waves and by calling attention to a factor which appears to play a significant rôle in the deepening of certain types of extra-tropical wave cyclones, viz. the variation with longitude of the basic current pattern.



Blocking Action in the Middle Troposphere and its Effect upon Regional Climate

I. An Aerological Study of Blocking Action

By DANIEL F. REX, University of Stockholm

(Manuscript received 10 August 1950)

Abstract

A comparative study of five cases of blocking action in the upper westerlies is presented with the two-fold objective of obtaining a more complete description of this phenomenon and of attempting an explanation of its initiation, development and dissipation in terms of parameters derived from an hydraulic analogue. The effect of European blocking upon the zonal and meridional circulation indices and the rôle of blocking in the evolution of hemispheric circulation patterns are discussed. In Part II, to be published later, the results of a preliminary semi-statistical analysis of blocking action, together with a description of the regional precipitation and mean surface-temperature anomalies produced by blocking, are presented. The statistical results obtained are discussed in relation to recent climatic fluktuations.

Characterization of atmospheric blocking

"Persistent anomalous meandering of the jet stream"

Rossby waves ↔ Macroturbulence

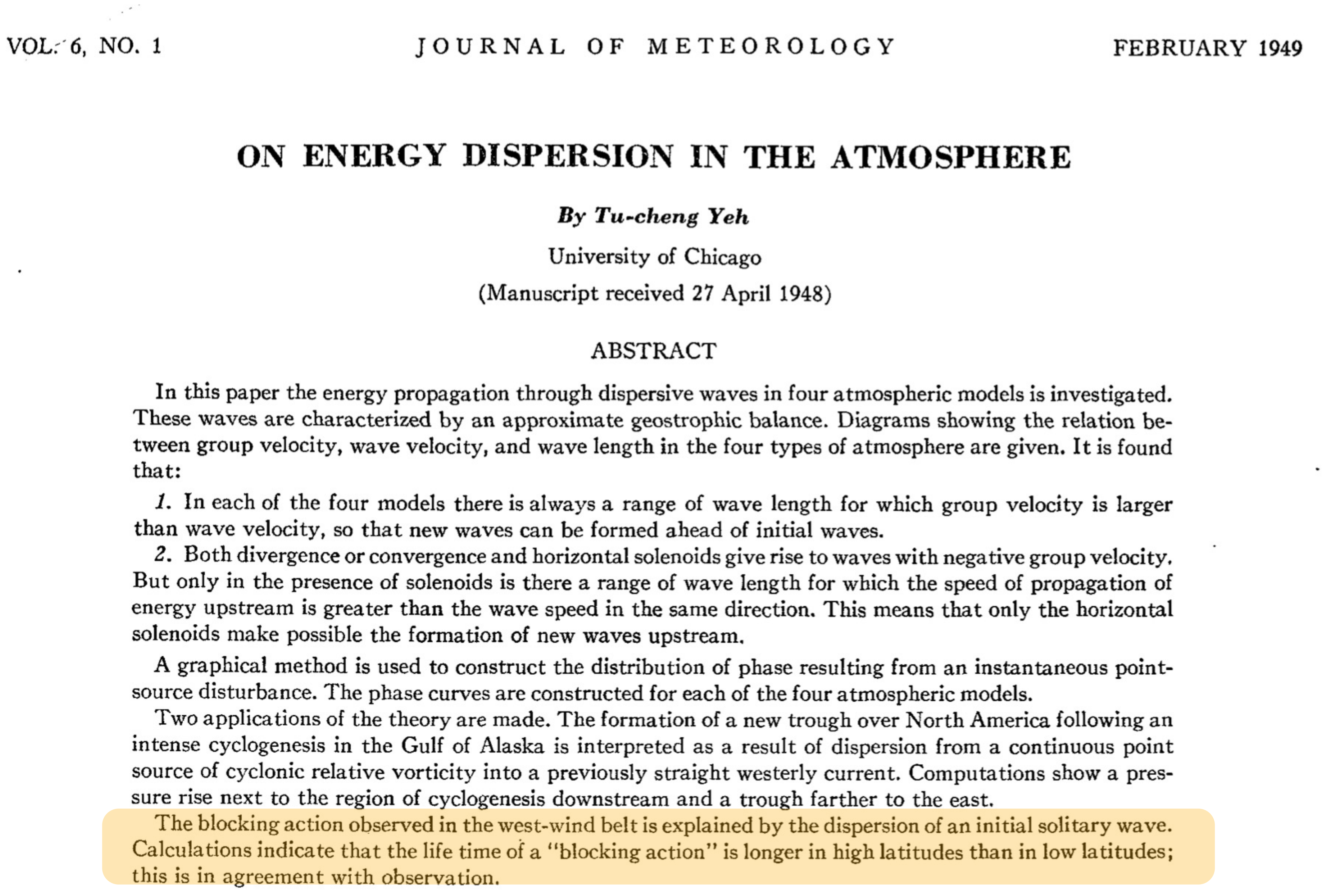
- Small-amplitude
- Dispersion relation

- Inverse cascade
- Barotropitization

- Finite-amplitude
- Scale interaction

- Deterministic chaos
- Weather regimes

Wave dispersion



VOL. 6, NO. 1 JOURNAL OF METEOROLOGY FEBRUARY 1949

ON ENERGY DISPERSION IN THE ATMOSPHERE

By Tu-cheng Yeh
University of Chicago

(Manuscript received 27 April 1948)

ABSTRACT

In this paper the energy propagation through dispersive waves in four atmospheric models is investigated. These waves are characterized by an approximate geostrophic balance. Diagrams showing the relation between group velocity, wave velocity, and wave length in the four types of atmosphere are given. It is found that:

1. In each of the four models there is always a range of wave length for which group velocity is larger than wave velocity, so that new waves can be formed ahead of initial waves.

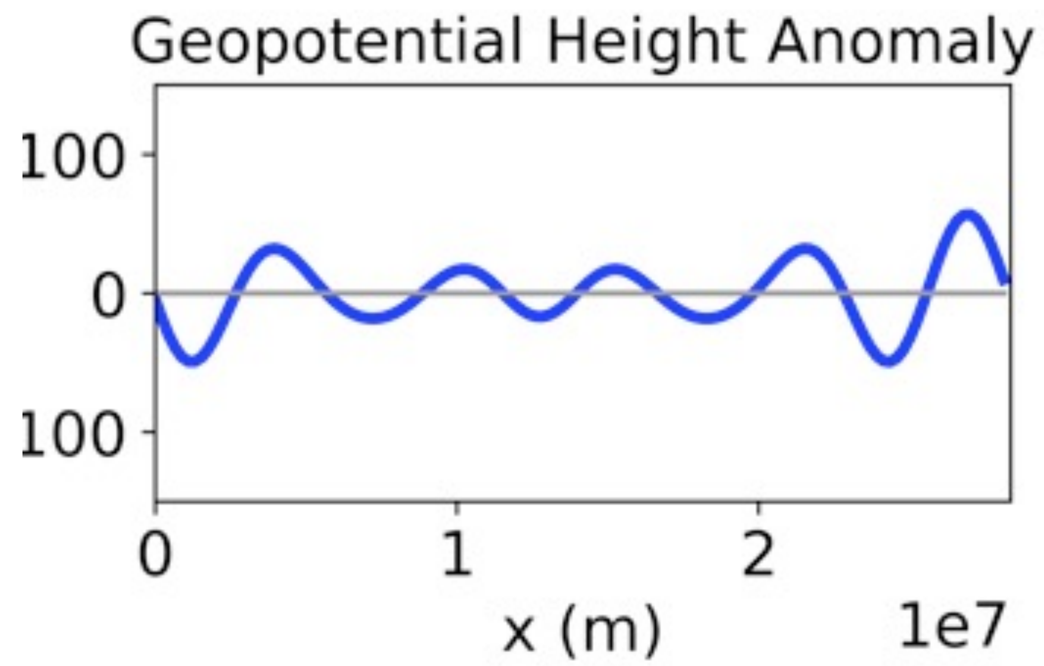
2. Both divergence or convergence and horizontal solenoids give rise to waves with negative group velocity. But only in the presence of solenoids is there a range of wave length for which the speed of propagation of energy upstream is greater than the wave speed in the same direction. This means that only the horizontal solenoids make possible the formation of new waves upstream.

A graphical method is used to construct the distribution of phase resulting from an instantaneous point-source disturbance. The phase curves are constructed for each of the four atmospheric models.

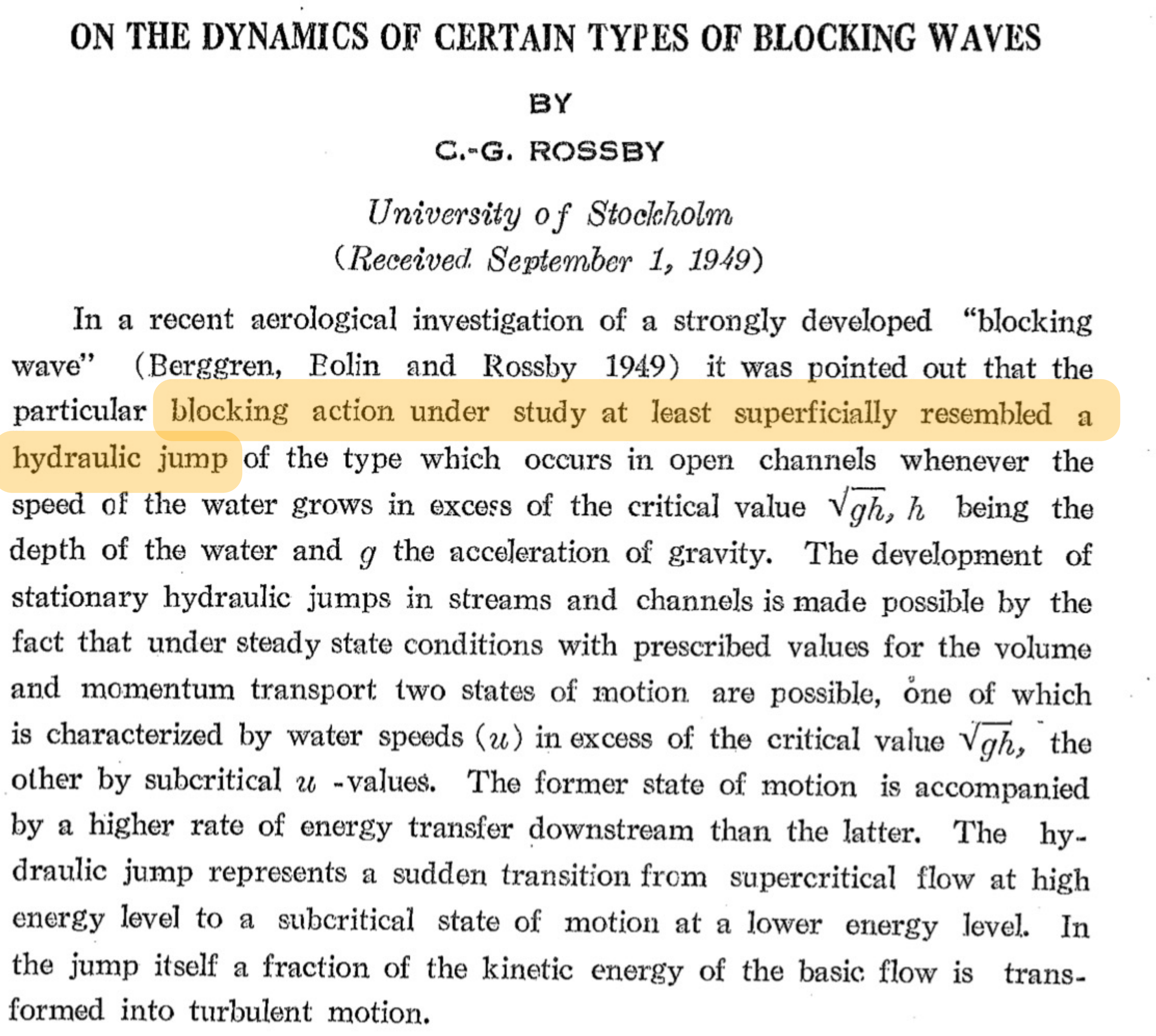
Two applications of the theory are made. The formation of a new trough over North America following an intense cyclogenesis in the Gulf of Alaska is interpreted as a result of dispersion from a continuous point source of cyclonic relative vorticity into a previously straight westerly current. Computations show a pressure rise next to the region of cyclogenesis downstream and a trough farther to the east.

The blocking action observed in the west-wind belt is explained by the dispersion of an initial solitary wave. Calculations indicate that the life time of a "blocking action" is longer in high latitudes than in low latitudes; this is in agreement with observation.

See also Lindzen (1986)



Hydraulic jump



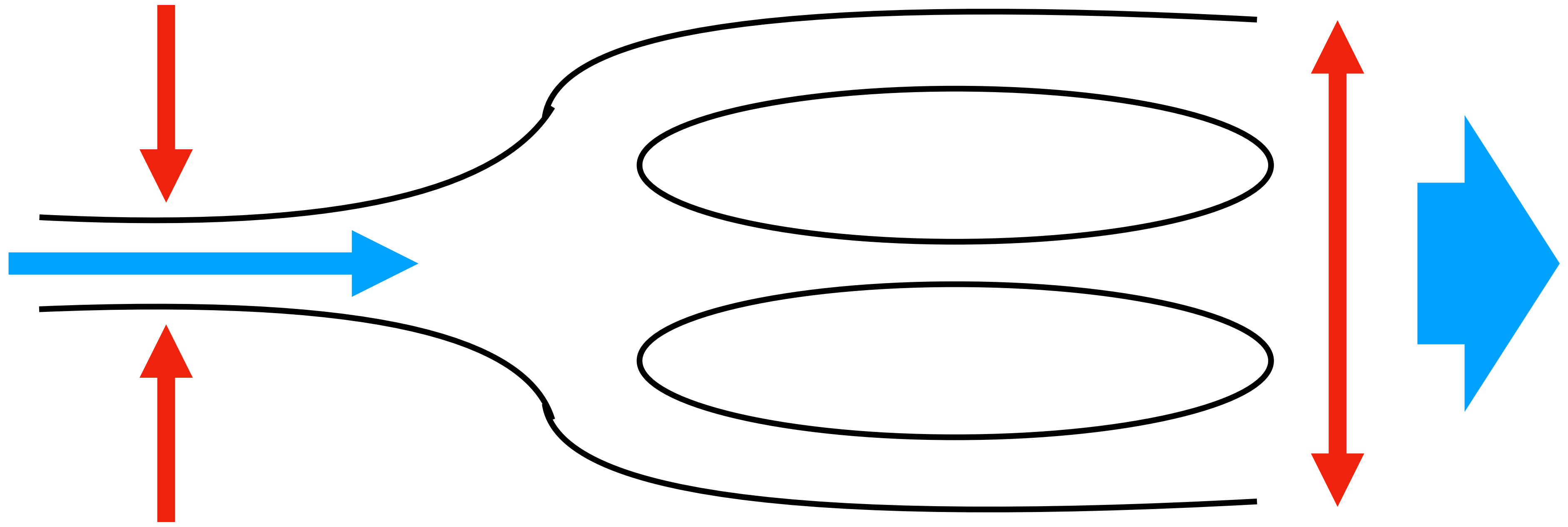
ON THE DYNAMICS OF CERTAIN TYPES OF BLOCKING WAVES

BY

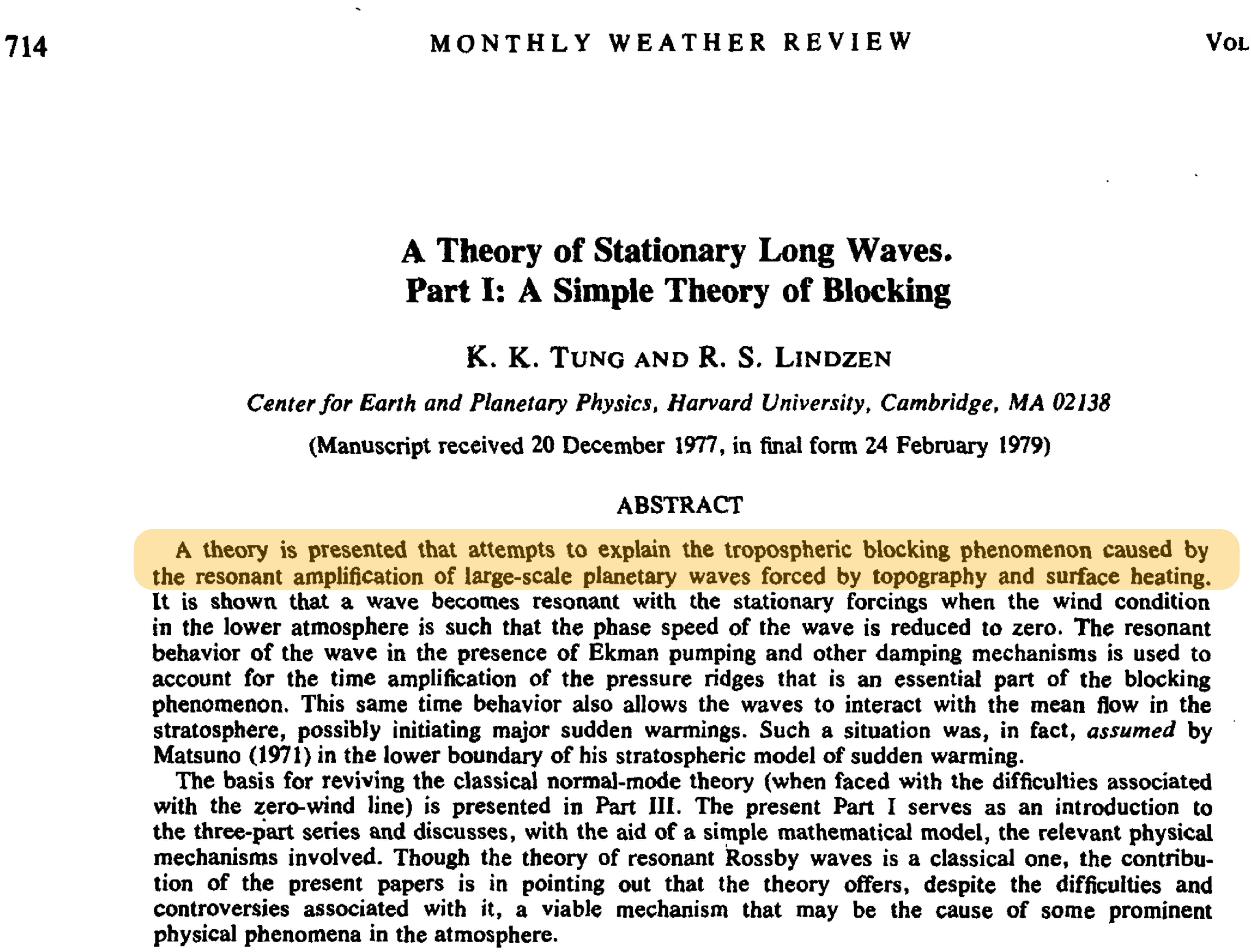
C.-G. ROSSBY

University of Stockholm
(*Received September 1, 1949*)

In a recent aerological investigation of a strongly developed "blocking wave" (Berggren, Bolin and Rossby 1949) it was pointed out that the particular blocking action under study at least superficially resembled a hydraulic jump of the type which occurs in open channels whenever the speed of the water grows in excess of the critical value $\sqrt{gh}$, h being the depth of the water and g the acceleration of gravity. The development of stationary hydraulic jumps in streams and channels is made possible by the fact that under steady state conditions with prescribed values for the volume and momentum transport two states of motion are possible, one of which is characterized by water speeds (u) in excess of the critical value $\sqrt{gh}$, the other by subcritical u-values. The former state of motion is accompanied by a higher rate of energy transfer downstream than the latter. The hydraulic jump represents a sudden transition from supercritical flow at high energy level to a subcritical state of motion at a lower energy level. In the jump itself a fraction of the kinetic energy of the basic flow is transformed into turbulent motion.



Wave resonance



714 MONTHLY WEATHER REVIEW VOLUME 107

A Theory of Stationary Long Waves.
Part I: A Simple Theory of Blocking

K. K. TUNG AND R. S. LINDZEN

Center for Earth and Planetary Physics, Harvard University, Cambridge, MA 02138

(Manuscript received 20 December 1977, in final form 24 February 1979)

ABSTRACT

A theory is presented that attempts to explain the tropospheric blocking phenomenon caused by the resonant amplification of large-scale planetary waves forced by topography and surface heating. It is shown that a wave becomes resonant with the stationary forcings when the wind condition in the lower atmosphere is such that the phase speed of the wave is reduced to zero. The resonant behavior of the wave in the presence of Ekman pumping and other damping mechanisms is used to account for the time amplification of the pressure ridges that is an essential part of the blocking phenomenon. This same time behavior also allows the waves to interact with the mean flow in the stratosphere, possibly initiating major sudden warmings. Such a situation was, in fact, *assumed* by Matsuno (1971) in the lower boundary of his stratospheric model of sudden warming.

The basis for reviving the classical normal-mode theory (when faced with the difficulties associated with the zero-wind line) is presented in Part III. The present Part I serves as an introduction to the three-part series and discusses, with the aid of a simple mathematical model, the relevant physical mechanisms involved. Though the theory of resonant Rossby waves is a classical one, the contribution of the present papers is in pointing out that the theory offers, despite the difficulties and controversies associated with it, a viable mechanism that may be the cause of some prominent physical phenomena in the atmosphere.

See also Petoukhov et al (2013)

THEORY OF STATIONARY EDDIES 131

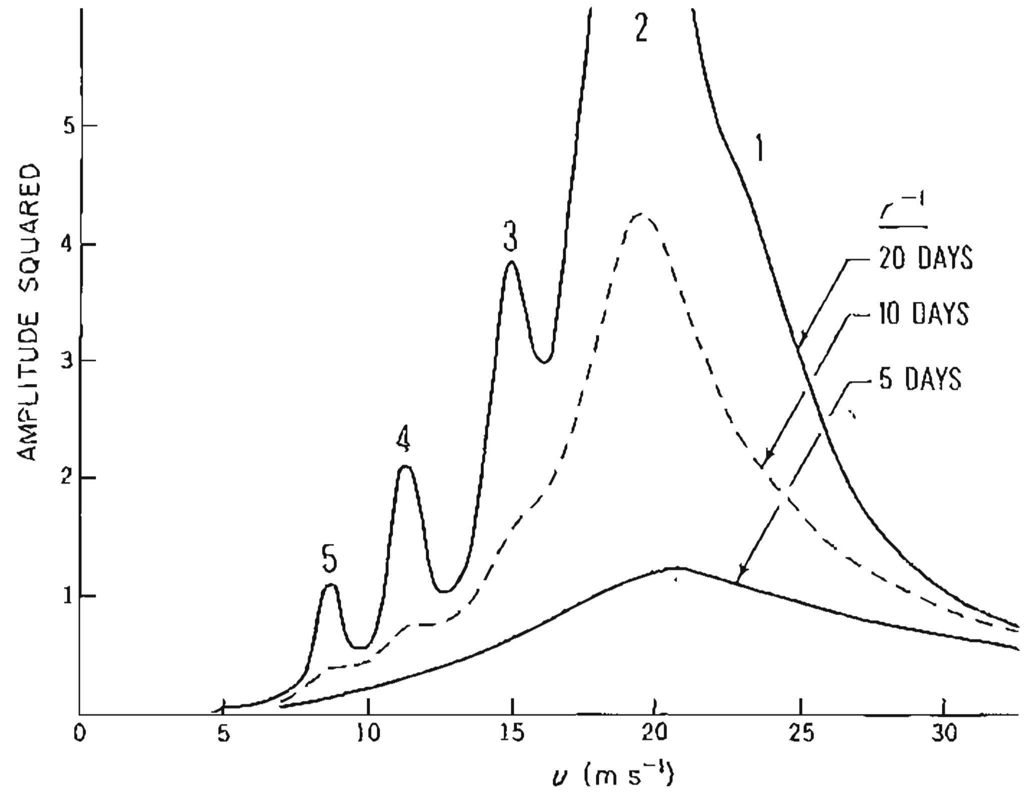
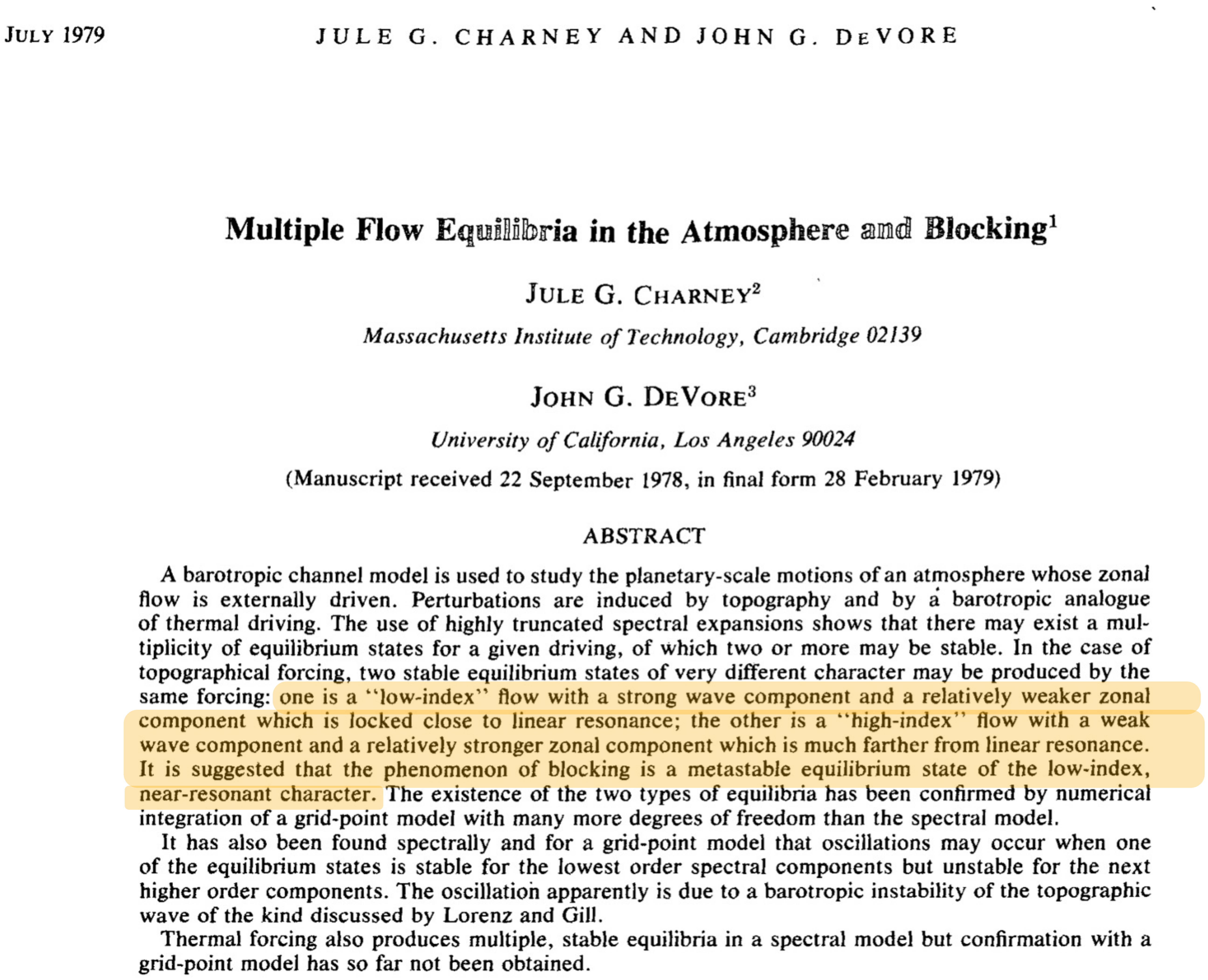


Fig. 6.1. The mean square height response, $[\eta^{*2}]$, in the Charney–Eliassen model as a function of $[u]$ for different strengths of dissipation, in units of 10^4 m^2. The integers mark the values of $[u]$ at which particular zonal wavenumbers resonate.

Weather regimes



JULY 1979 JULE G. CHARNEY AND JOHN G. DEVORE

Multiple Flow Equilibria in the Atmosphere and Blocking[1]

JULE G. CHARNEY[2]
Massachusetts Institute of Technology, Cambridge 02139

JOHN G. DEVORE[3]
University of California, Los Angeles 90024

(Manuscript received 22 September 1978, in final form 28 February 1979)

ABSTRACT

A barotropic channel model is used to study the planetary-scale motions of an atmosphere whose zonal flow is externally driven. Perturbations are induced by topography and by a barotropic analogue of thermal driving. The use of highly truncated spectral expansions shows that there may exist a multiplicity of equilibrium states for a given driving, of which two or more may be stable. In the case of topographical forcing, two stable equilibrium states of very different character may be produced by the same forcing: one is a "low-index" flow with a strong wave component and a relatively weaker zonal component which is locked close to linear resonance; the other is a "high-index" flow with a weak wave component and a relatively stronger zonal component which is much farther from linear resonance. It is suggested that the phenomenon of blocking is a metastable equilibrium state of the low-index, near-resonant character. The existence of the two types of equilibria has been confirmed by numerical integration of a grid-point model with many more degrees of freedom than the spectral model.

It has also been found spectrally and for a grid-point model that oscillations may occur when one of the equilibrium states is stable for the lowest order spectral components but unstable for the next higher order components. The oscillation apparently is due to a barotropic instability of the topographic wave of the kind discussed by Lorenz and Gill.

Thermal forcing also produces multiple, stable equilibria in a spectral model but confirmation with a grid-point model has so far not been obtained.

134 I. M. HELD

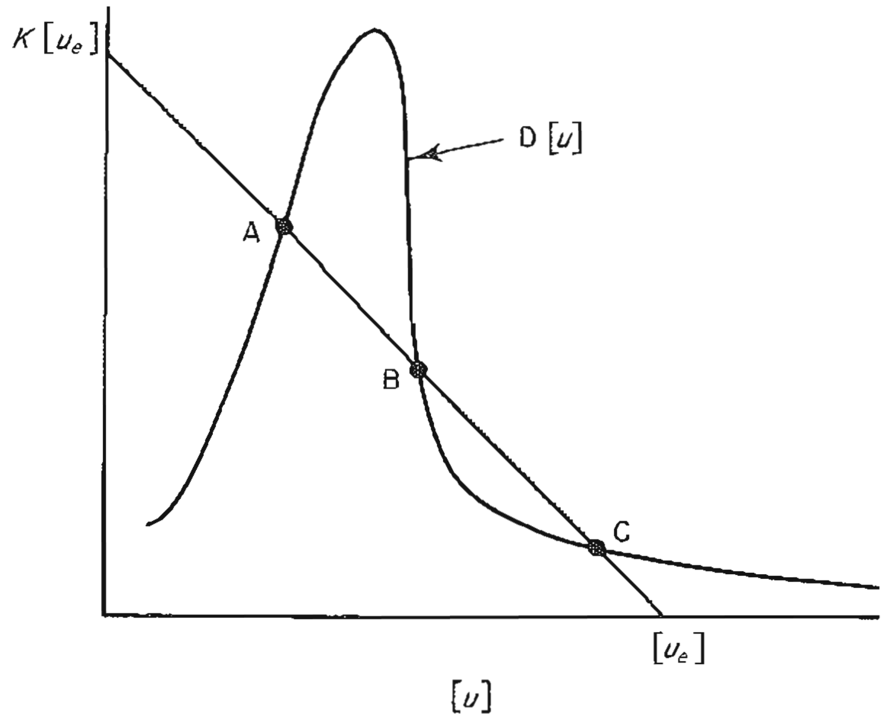
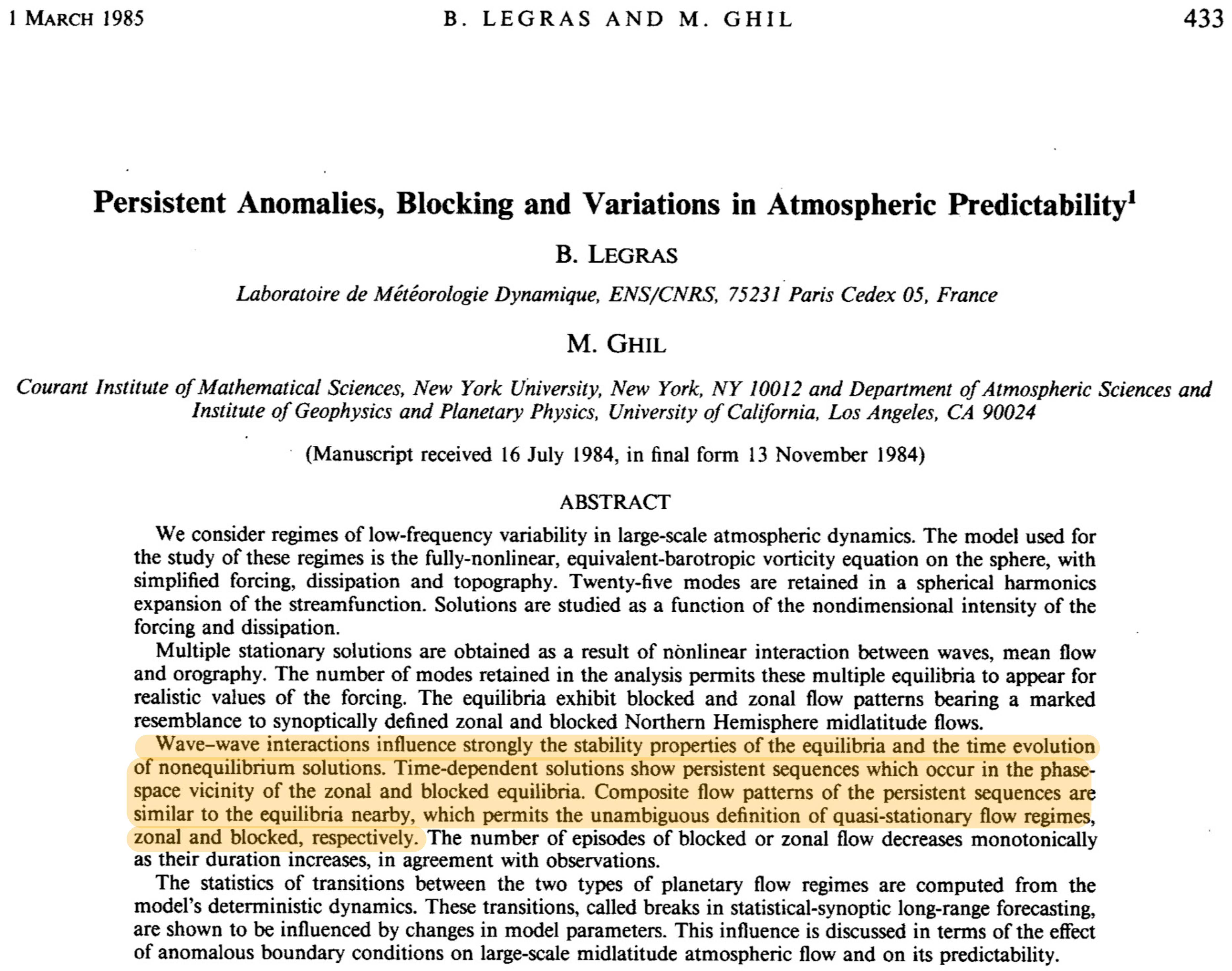


Fig. 6.4. A schematic of the graphic solution for the equilibrium states in the Charney–DeVore model.

Deterministic chaos



Persistent Anomalies, Blocking and Variations in Atmospheric Predictability[1]

B. LEGRAS
Laboratoire de Météorologie Dynamique, ENS/CNRS, 75231 Paris Cedex 05, France

M. GHIL
Courant Institute of Mathematical Sciences, New York University, New York, NY 10012 and Department of Atmospheric Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024

(Manuscript received 16 July 1984, in final form 13 November 1984)

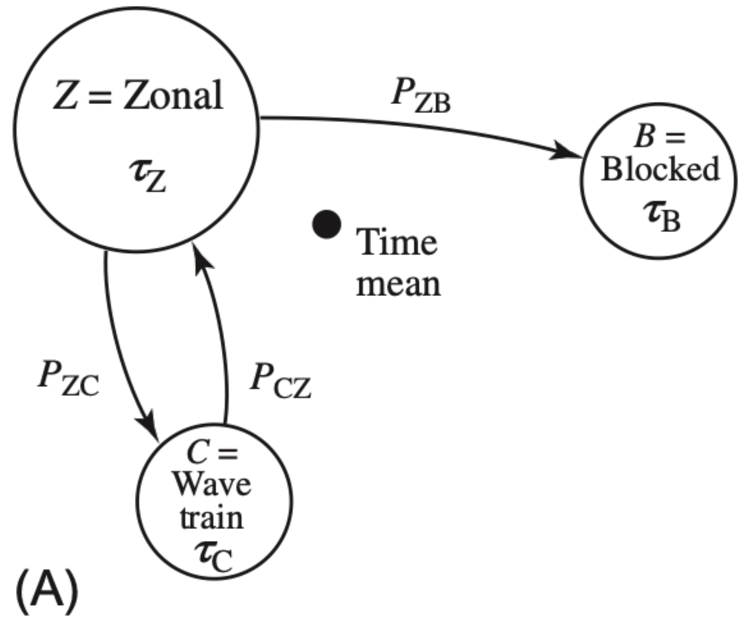
ABSTRACT

We consider regimes of low-frequency variability in large-scale atmospheric dynamics. The model used for the study of these regimes is the fully-nonlinear, equivalent-barotropic vorticity equation on the sphere, with simplified forcing, dissipation and topography. Twenty-five modes are retained in a spherical harmonics expansion of the streamfunction. Solutions are studied as a function of the nondimensional intensity of the forcing and dissipation.

Multiple stationary solutions are obtained as a result of nonlinear interaction between waves, mean flow and orography. The number of modes retained in the analysis permits these multiple equilibria to appear for realistic values of the forcing. The equilibria exhibit blocked and zonal flow patterns bearing a marked resemblance to synoptically defined zonal and blocked Northern Hemisphere midlatitude flows.

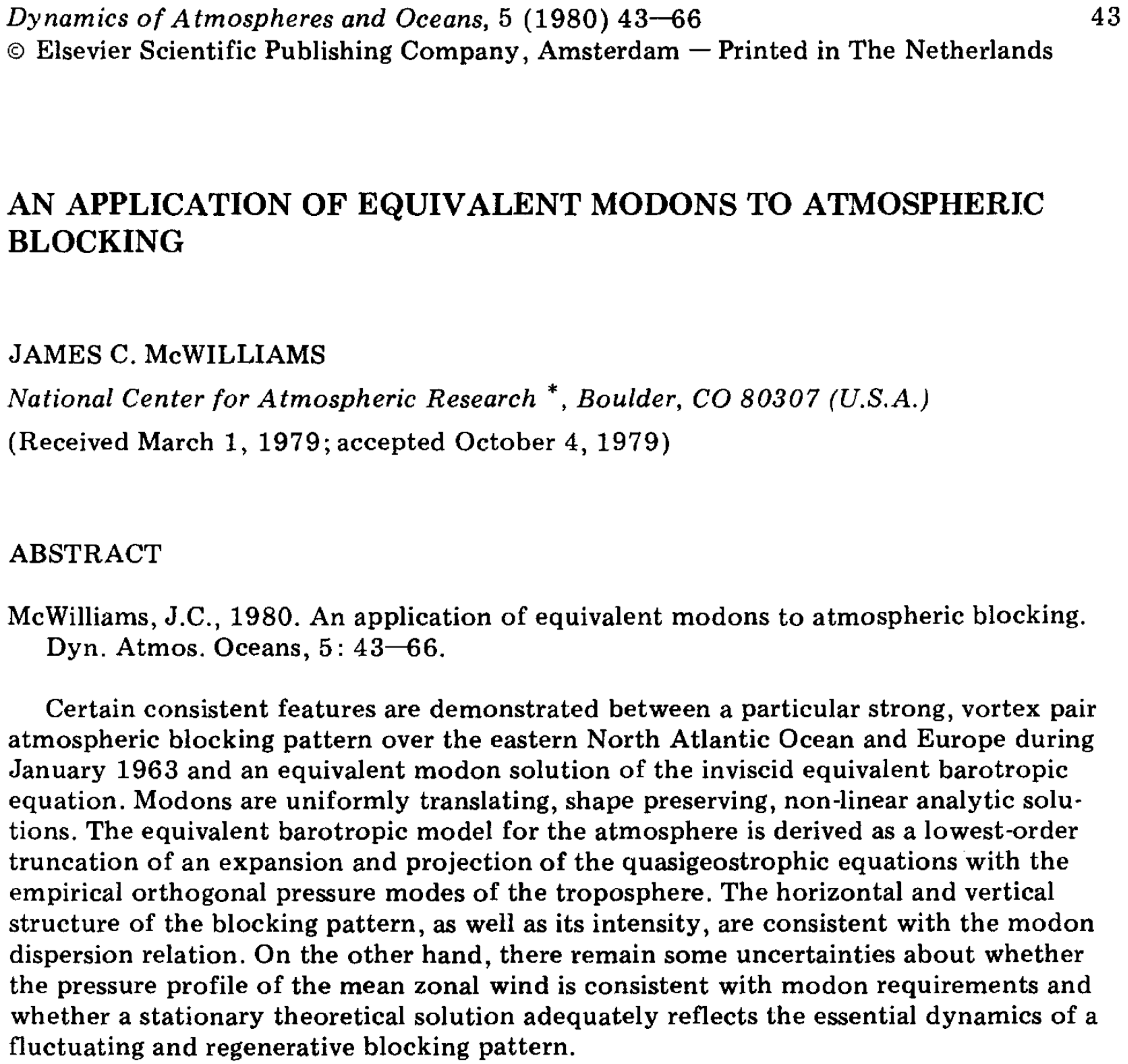
Wave–wave interactions influence strongly the stability properties of the equilibria and the time evolution of nonequilibrium solutions. Time-dependent solutions show persistent sequences which occur in the phase-space vicinity of the zonal and blocked equilibria. Composite flow patterns of the persistent sequences are similar to the equilibria nearby, which permits the unambiguous definition of quasi-stationary flow regimes, zonal and blocked, respectively. The number of episodes of blocked or zonal flow decreases monotonically as their duration increases, in agreement with observations.

The statistics of transitions between the two types of planetary flow regimes are computed from the model's deterministic dynamics. These transitions, called breaks in statistical-synoptic long-range forecasting, are shown to be influenced by changes in model parameters. This influence is discussed in terms of the effect of anomalous boundary conditions on large-scale midlatitude atmospheric flow and on its predictability.



See also Ghil et al (2018, 2020), Lucarini and Gritsun (2020)

Modons



Dynamics of Atmospheres and Oceans, 5 (1980) 43—66 43
© Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

AN APPLICATION OF EQUIVALENT MODONS TO ATMOSPHERIC BLOCKING

JAMES C. McWILLIAMS

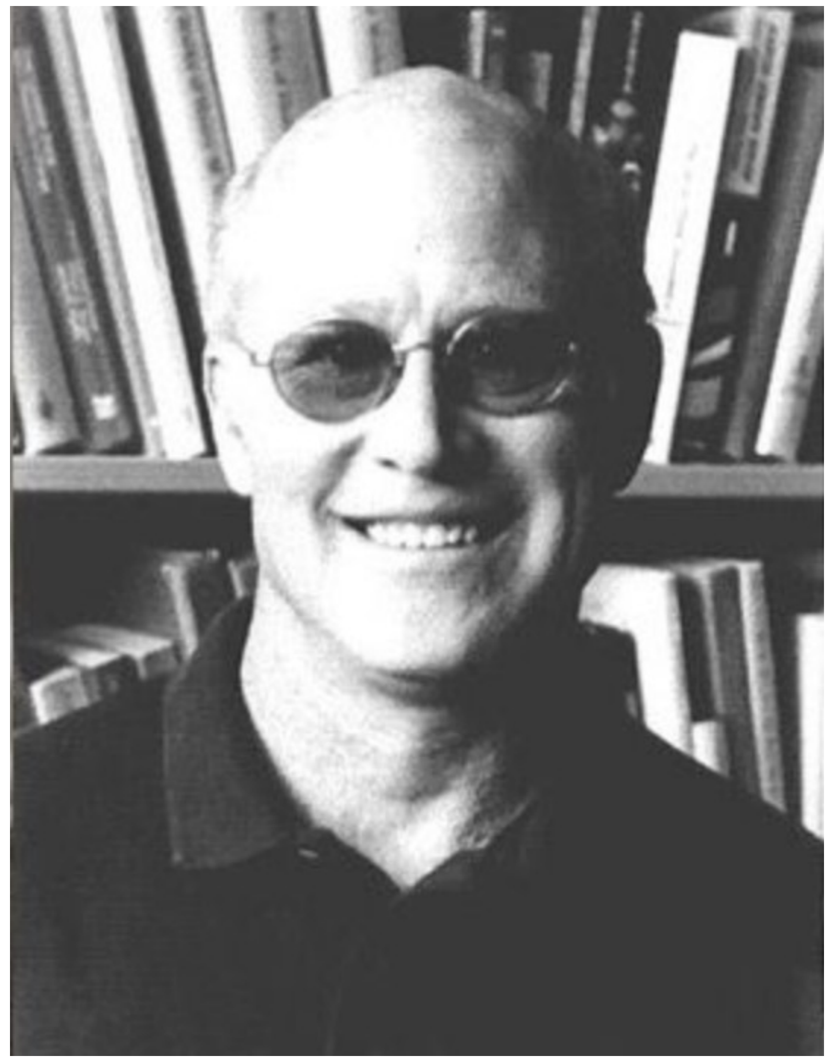
National Center for Atmospheric Research *, *Boulder, CO 80307 (U.S.A.)*

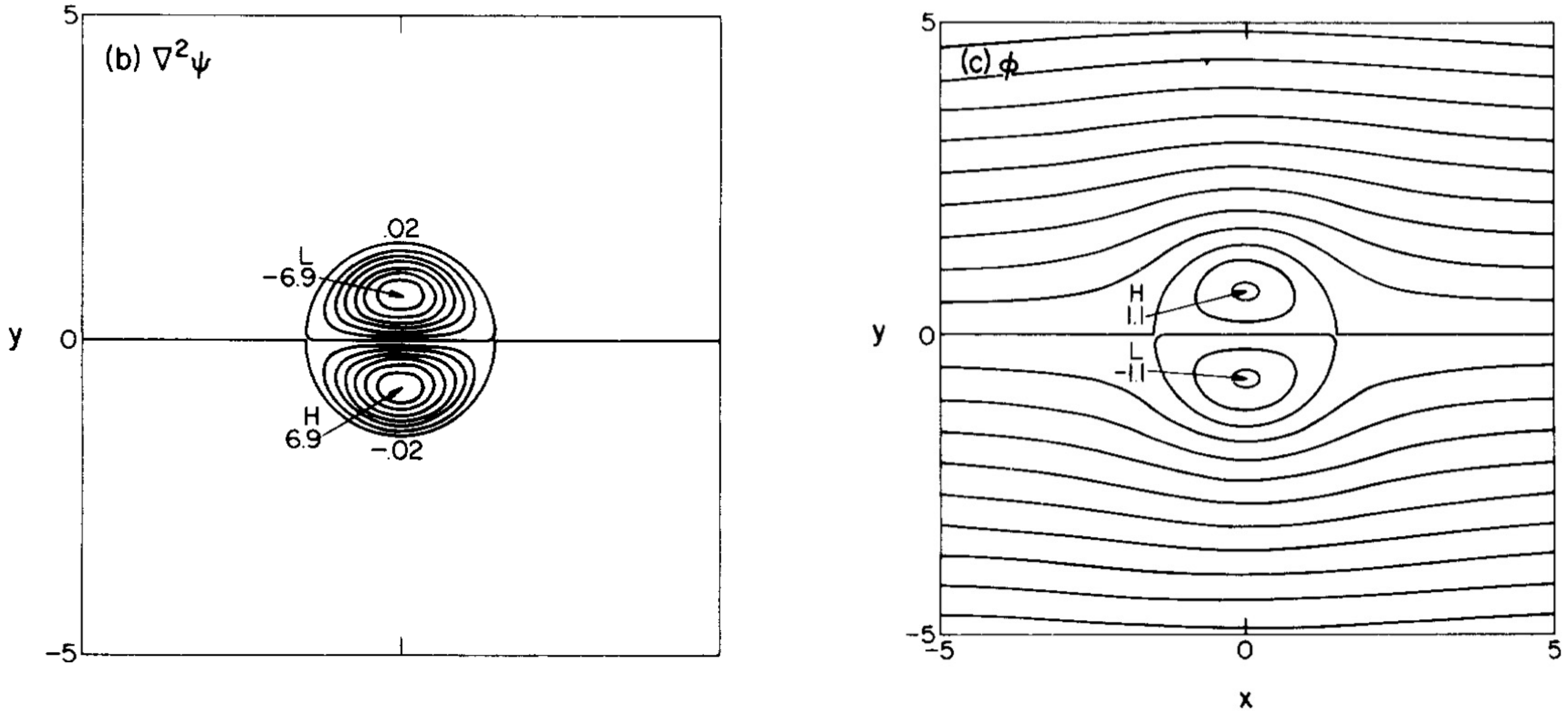
(Received March 1, 1979; accepted October 4, 1979)

ABSTRACT

McWilliams, J.C., 1980. An application of equivalent modons to atmospheric blocking. Dyn. Atmos. Oceans, 5: 43—66.

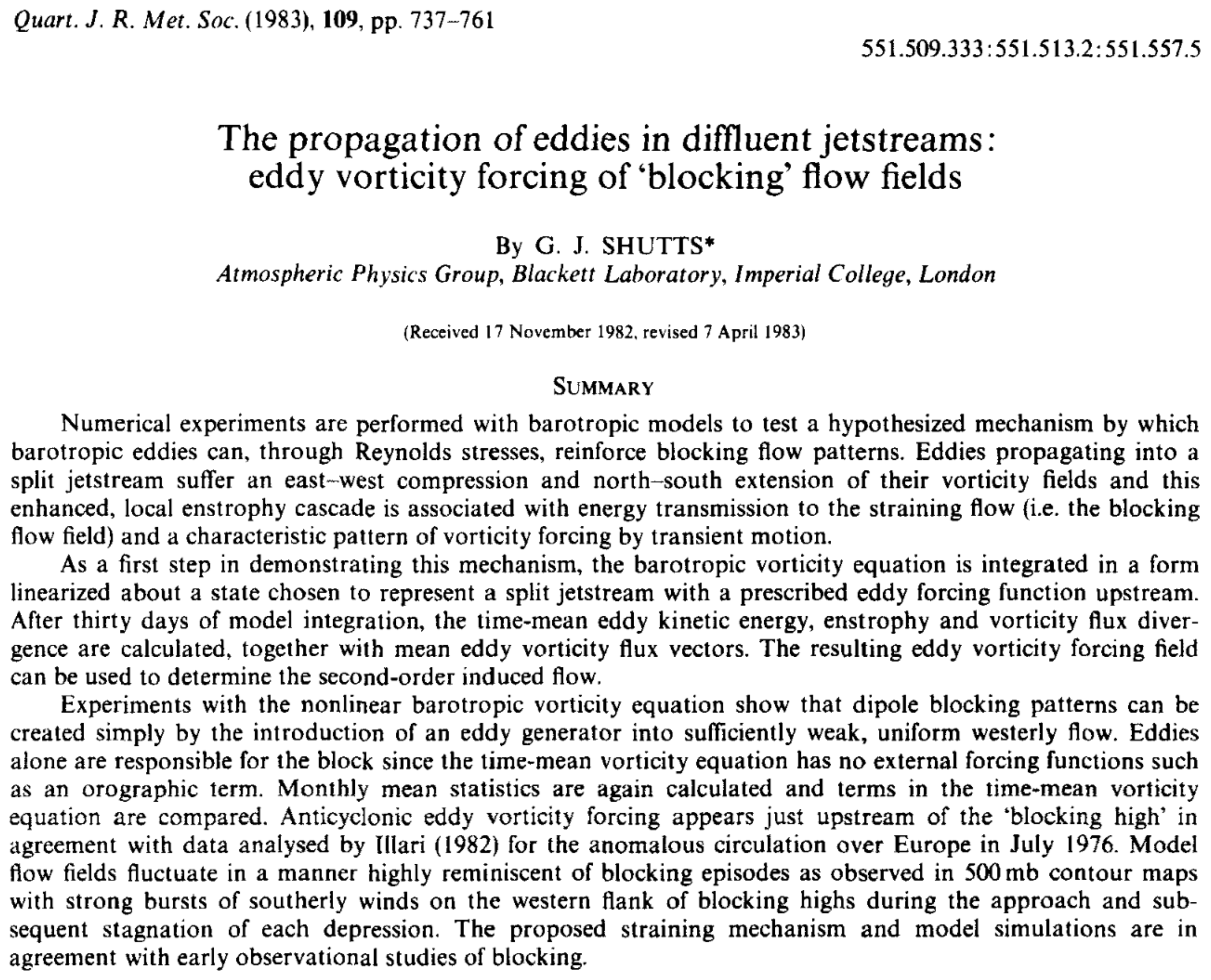
Certain consistent features are demonstrated between a particular strong, vortex pair atmospheric blocking pattern over the eastern North Atlantic Ocean and Europe during January 1963 and an equivalent modon solution of the inviscid equivalent barotropic equation. Modons are uniformly translating, shape preserving, non-linear analytic solutions. The equivalent barotropic model for the atmosphere is derived as a lowest-order truncation of an expansion and projection of the quasigeostrophic equations with the empirical orthogonal pressure modes of the troposphere. The horizontal and vertical structure of the blocking pattern, as well as its intensity, are consistent with the modon dispersion relation. On the other hand, there remain some uncertainties about whether the pressure profile of the mean zonal wind is consistent with modon requirements and whether a stationary theoretical solution adequately reflects the essential dynamics of a fluctuating and regenerative blocking pattern.





See also Haines and Marshall (1987) and Butchart et al. (1989)

Scale interaction (maintenance)



Quart. J. R. Met. Soc. (1983), **109**, pp. 737–761

551.509.333:551.513.2:551.557.5

The propagation of eddies in diffluent jetstreams: eddy vorticity forcing of 'blocking' flow fields

By G. J. SHUTTS*
Atmospheric Physics Group, Blackett Laboratory, Imperial College, London

(Received 17 November 1982, revised 7 April 1983)

SUMMARY

Numerical experiments are performed with barotropic models to test a hypothesized mechanism by which barotropic eddies can, through Reynolds stresses, reinforce blocking flow patterns. Eddies propagating into a split jetstream suffer an east–west compression and north–south extension of their vorticity fields and this enhanced, local enstrophy cascade is associated with energy transmission to the straining flow (i.e. the blocking flow field) and a characteristic pattern of vorticity forcing by transient motion.

As a first step in demonstrating this mechanism, the barotropic vorticity equation is integrated in a form linearized about a state chosen to represent a split jetstream with a prescribed eddy forcing function upstream. After thirty days of model integration, the time-mean eddy kinetic energy, enstrophy and vorticity flux divergence are calculated, together with mean eddy vorticity flux vectors. The resulting eddy vorticity forcing field can be used to determine the second-order induced flow.

Experiments with the nonlinear barotropic vorticity equation show that dipole blocking patterns can be created simply by the introduction of an eddy generator into sufficiently weak, uniform westerly flow. Eddies alone are responsible for the block since the time-mean vorticity equation has no external forcing functions such as an orographic term. Monthly mean statistics are again calculated and terms in the time-mean vorticity equation are compared. Anticyclonic eddy vorticity forcing appears just upstream of the 'blocking high' in agreement with data analysed by Illari (1982) for the anomalous circulation over Europe in July 1976. Model flow fields fluctuate in a manner highly reminiscent of blocking episodes as observed in 500 mb contour maps with strong bursts of southerly winds on the western flank of blocking highs during the approach and subsequent stagnation of each depression. The proposed straining mechanism and model simulations are in agreement with early observational studies of blocking.

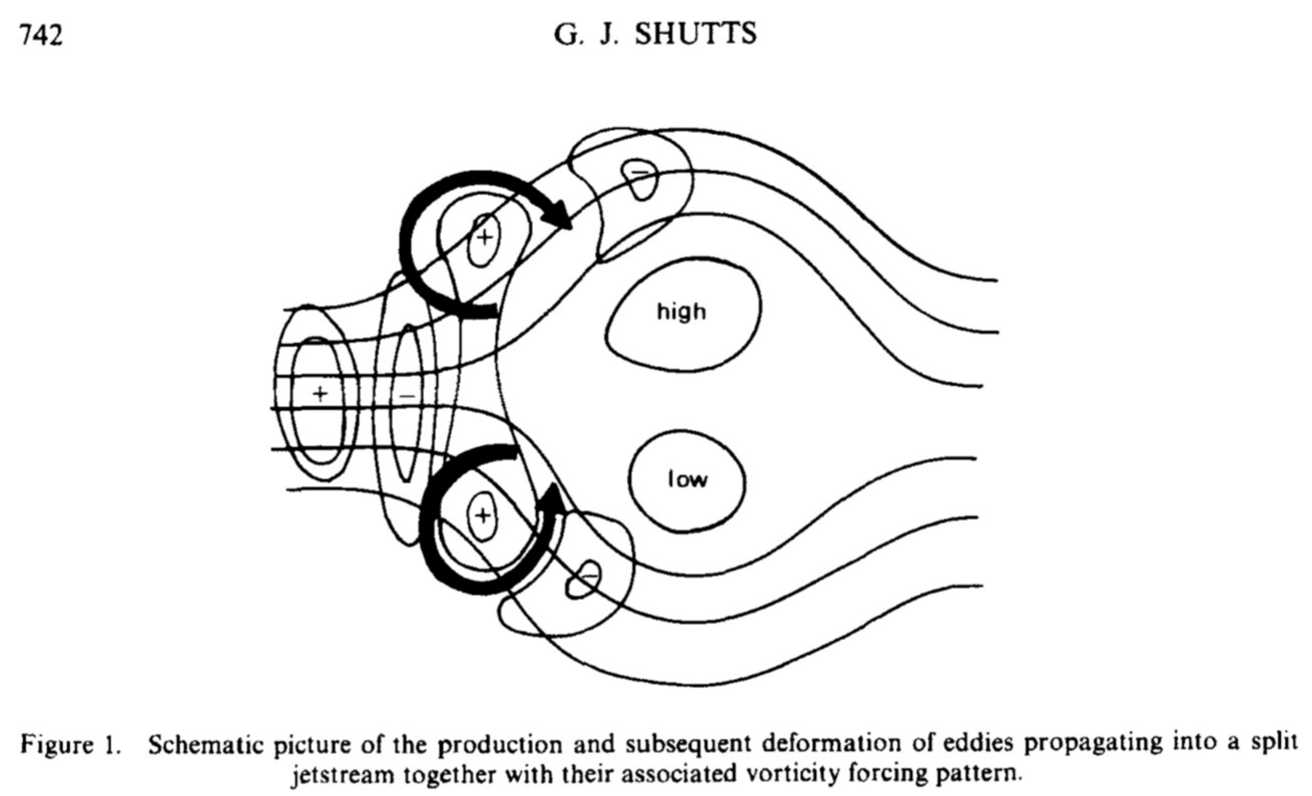
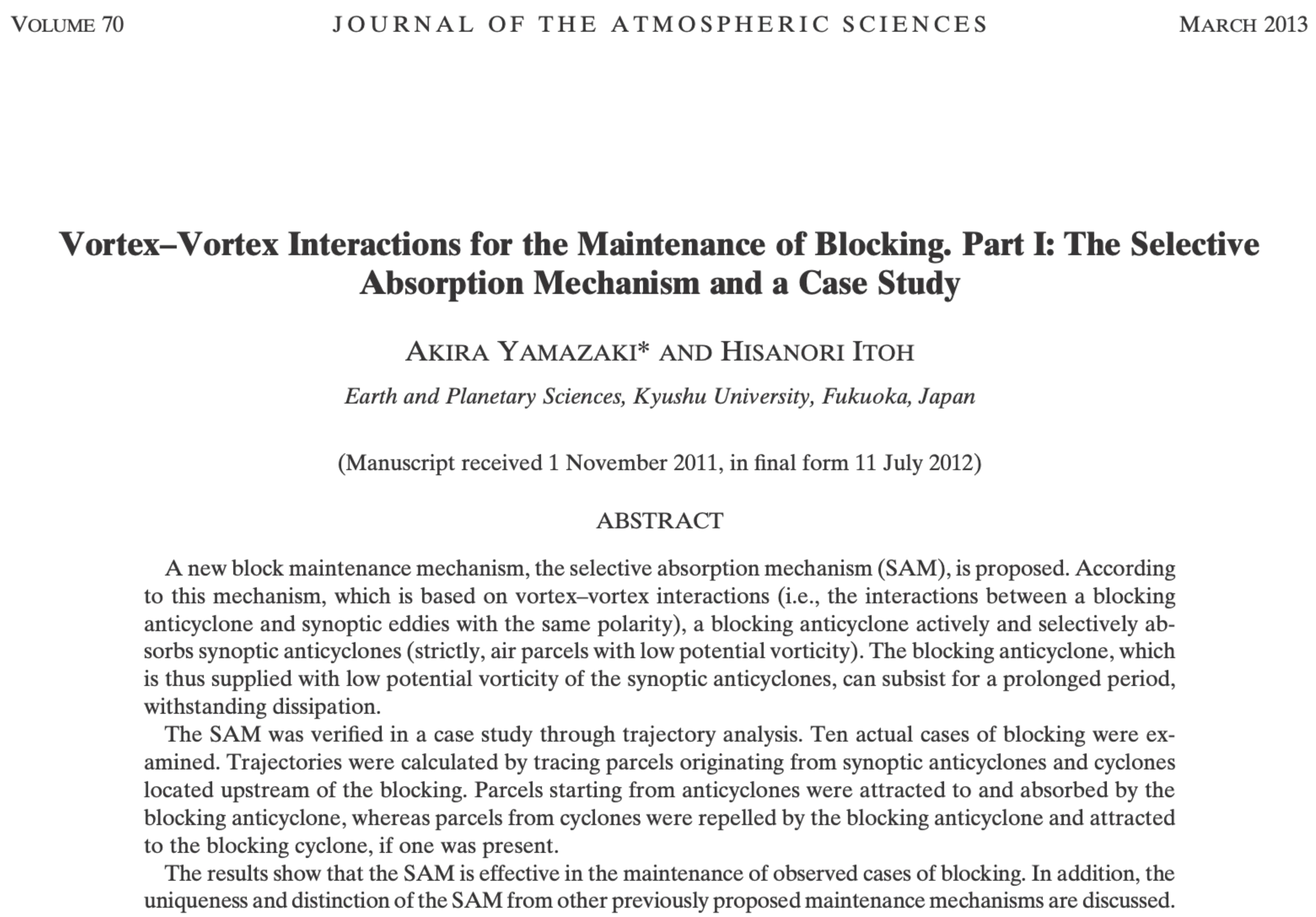


Figure 1. Schematic picture of the production and subsequent deformation of eddies propagating into a split jetstream together with their associated vorticity forcing pattern.



VOLUME 70 JOURNAL OF THE ATMOSPHERIC SCIENCES MARCH 2013

Vortex–Vortex Interactions for the Maintenance of Blocking. Part I: The Selective Absorption Mechanism and a Case Study

AKIRA YAMAZAKI* AND HISANORI ITOH
Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan

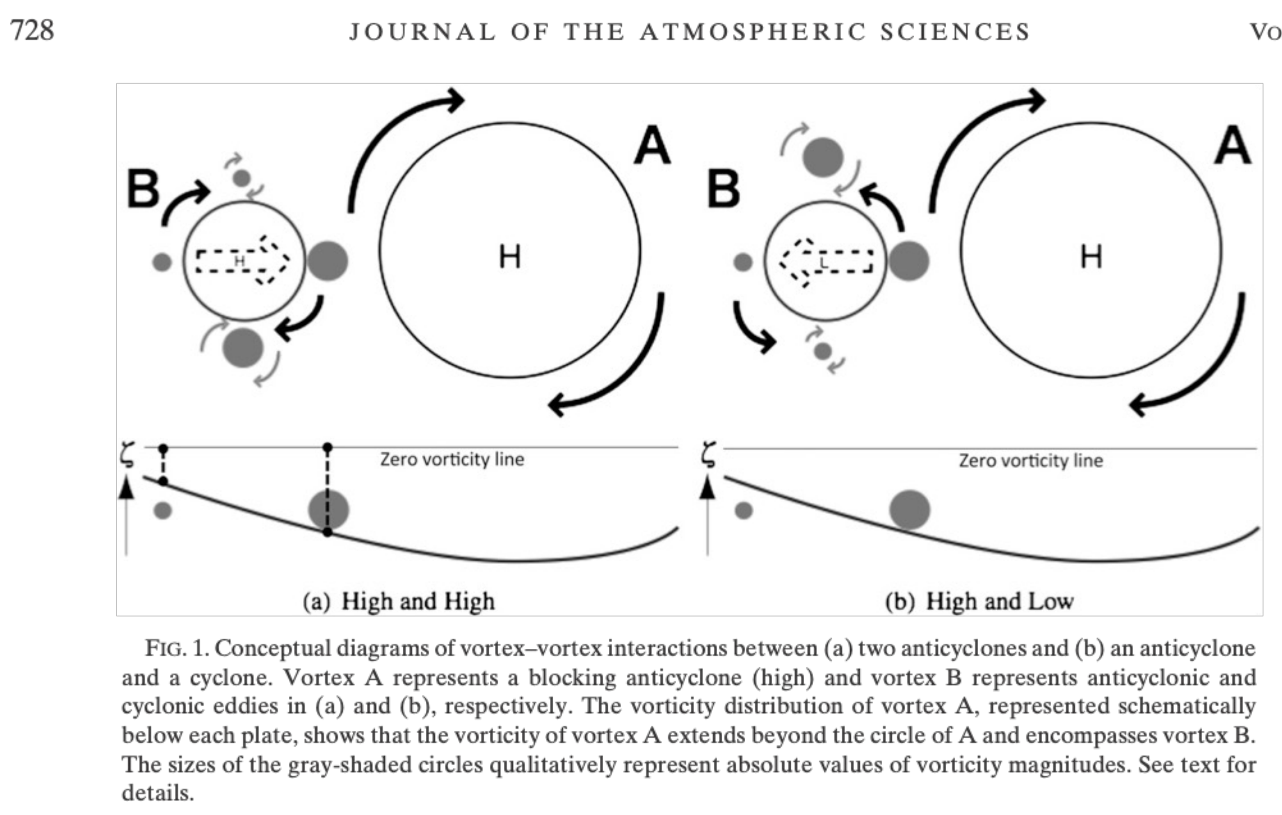
(Manuscript received 1 November 2011, in final form 11 July 2012)

ABSTRACT

A new block maintenance mechanism, the selective absorption mechanism (SAM), is proposed. According to this mechanism, which is based on vortex–vortex interactions (i.e., the interactions between a blocking anticyclone and synoptic eddies with the same polarity), a blocking anticyclone actively and selectively absorbs synoptic anticyclones (strictly, air parcels with low potential vorticity). The blocking anticyclone, which is thus supplied with low potential vorticity of the synoptic anticyclones, can subsist for a prolonged period, withstanding dissipation.

The SAM was verified in a case study through trajectory analysis. Ten actual cases of blocking were examined. Trajectories were calculated by tracing parcels originating from synoptic anticyclones and cyclones located upstream of the blocking. Parcels starting from anticyclones were attracted to and absorbed by the blocking anticyclone, whereas parcels from cyclones were repelled by the blocking anticyclone and attracted to the blocking cyclone, if one was present.

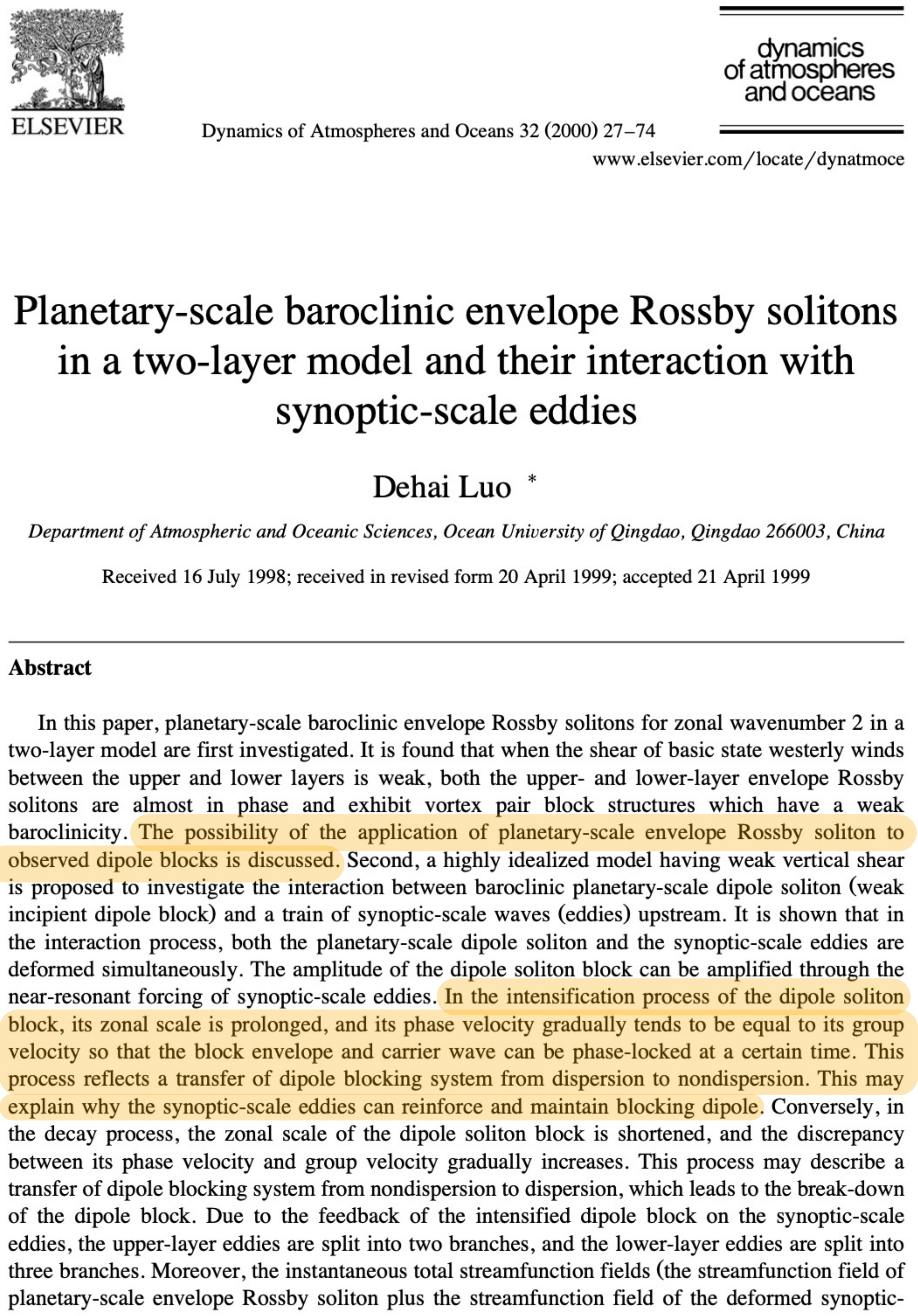
The results show that the SAM is effective in the maintenance of observed cases of blocking. In addition, the uniqueness and distinction of the SAM from other previously proposed maintenance mechanisms are discussed.



(a) High and High (b) High and Low

FIG. 1. Conceptual diagrams of vortex–vortex interactions between (a) two anticyclones and (b) an anticyclone and a cyclone. Vortex A represents a blocking anticyclone (high) and vortex B represents anticyclonic and cyclonic eddies in (a) and (b), respectively. The vorticity distribution of vortex A, represented schematically below each plate, shows that the vorticity of vortex A extends beyond the circle of A and encompasses vortex B. The sizes of the gray-shaded circles qualitatively represent absolute values of vorticity magnitudes. See text for details.

Scale interaction (lifecycle)



ELSEVIER

Dynamics of Atmospheres and Oceans 32 (2000) 27–74

dynamics
of atmospheres
and oceans

www.elsevier.com/locate/dynatmoce

Planetary-scale baroclinic envelope Rossby solitons in a two-layer model and their interaction with synoptic-scale eddies

Dehai Luo *

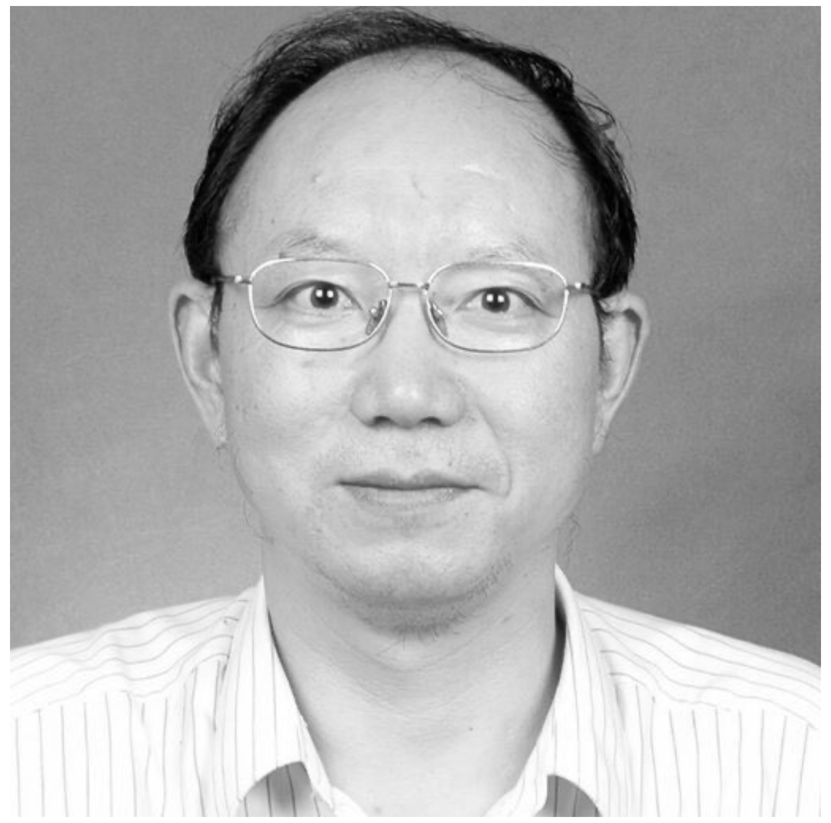
Department of Atmospheric and Oceanic Sciences, Ocean University of Qingdao, Qingdao 266003, China

Received 16 July 1998; received in revised form 20 April 1999; accepted 21 April 1999

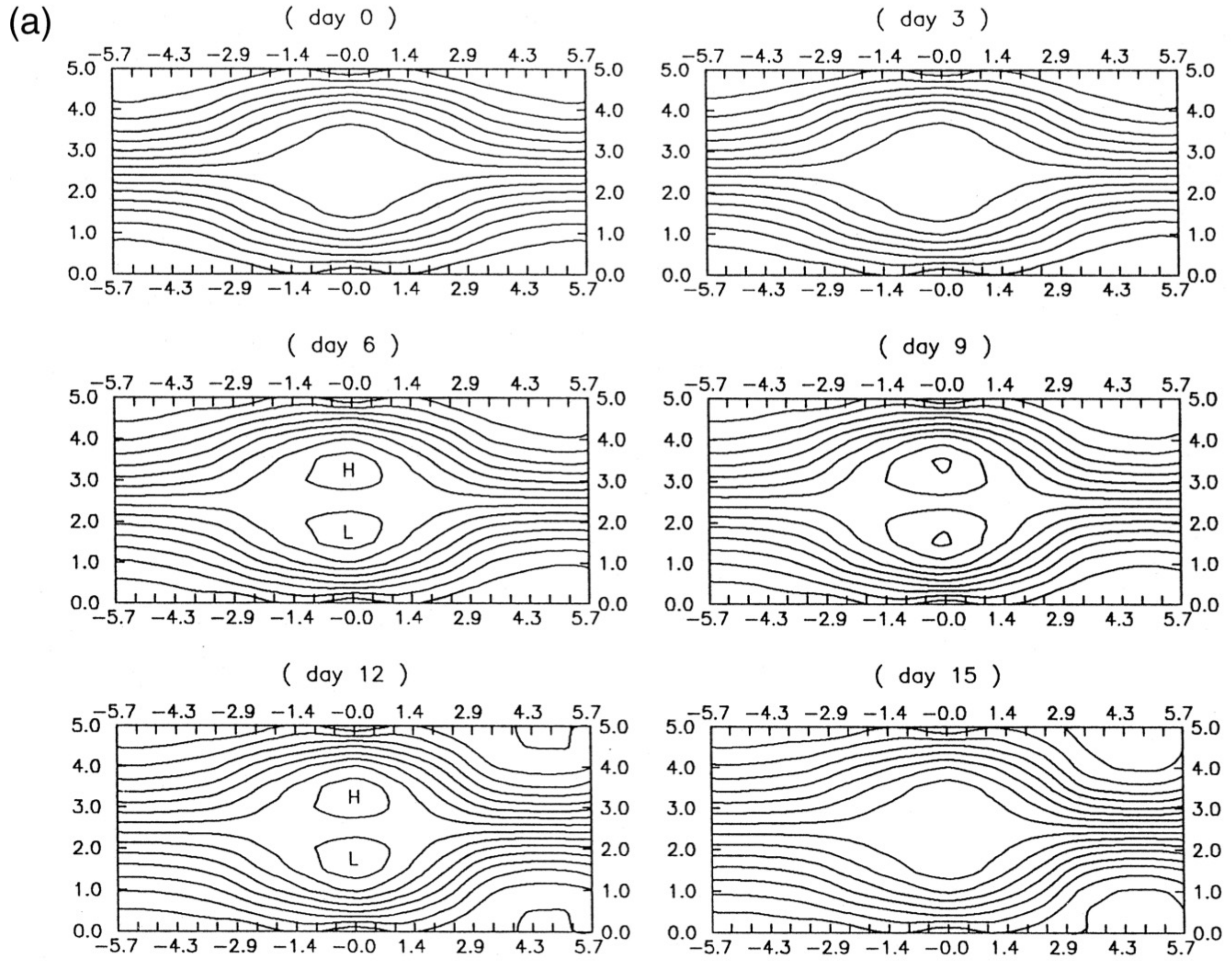
Abstract

In this paper, planetary-scale baroclinic envelope Rossby solitons for zonal wavenumber 2 in a two-layer model are first investigated. It is found that when the shear of basic state westerly winds between the upper and lower layers is weak, both the upper- and lower-layer envelope Rossby solitons are almost in phase and exhibit vortex pair block structures which have a weak baroclinicity. The possibility of the application of planetary-scale envelope Rossby soliton to observed dipole blocks is discussed. Second, a highly idealized model having weak vertical shear is proposed to investigate the interaction between baroclinic planetary-scale dipole soliton (weak incipient dipole block) and a train of synoptic-scale waves (eddies) upstream. It is shown that in the interaction process, both the planetary-scale dipole soliton and the synoptic-scale eddies are deformed simultaneously. The amplitude of the dipole soliton block can be amplified through the near-resonant forcing of synoptic-scale eddies. In the intensification process of the dipole soliton block, its zonal scale is prolonged, and its phase velocity gradually tends to be equal to its group velocity so that the block envelope and carrier wave can be phase-locked at a certain time. This process reflects a transfer of dipole blocking system from dispersion to nondispersion. This may explain why the synoptic-scale eddies can reinforce and maintain blocking dipole. Conversely, in the decay process, the zonal scale of the dipole soliton block is shortened, and the discrepancy between its phase velocity and group velocity gradually increases. This process may describe a transfer of dipole blocking system from nondispersion to dispersion, which leads to the break-down of the dipole block. Due to the feedback of the intensified dipole block on the synoptic-scale eddies, the upper-layer eddies are split into two branches, and the lower-layer eddies are split into three branches. Moreover, the instantaneous total streamfunction fields (the streamfunction field of planetary-scale envelope Rossby soliton plus the streamfunction field of the deformed synoptic-

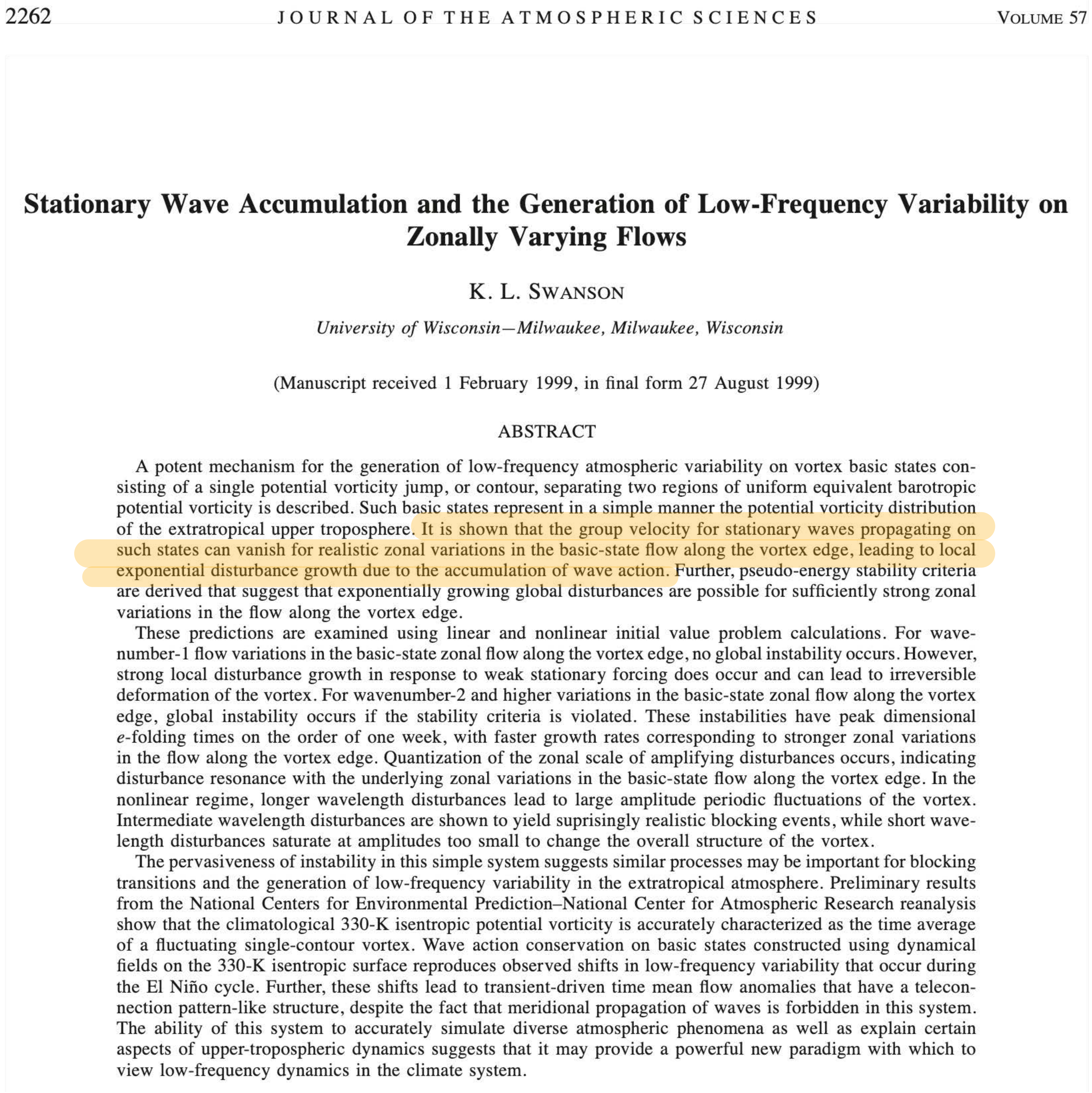
See also H. Nakamura et. al (1997)



$$i\frac{\partial B}{\partial T}+\frac{1}{2}\frac{\partial^2 B}{\partial \xi^2}+|B|^2B+\sqrt{\delta}\,\hbar f_0'^2\exp[-i(\Delta\kappa X_1+\Omega T_1)]=0. \qquad (30)$$



Local instability of a stationary wave



Stationary Wave Accumulation and the Generation of Low-Frequency Variability on Zonally Varying Flows

K. L. SWANSON

University of Wisconsin—Milwaukee, Milwaukee, Wisconsin

(Manuscript received 1 February 1999, in final form 27 August 1999)

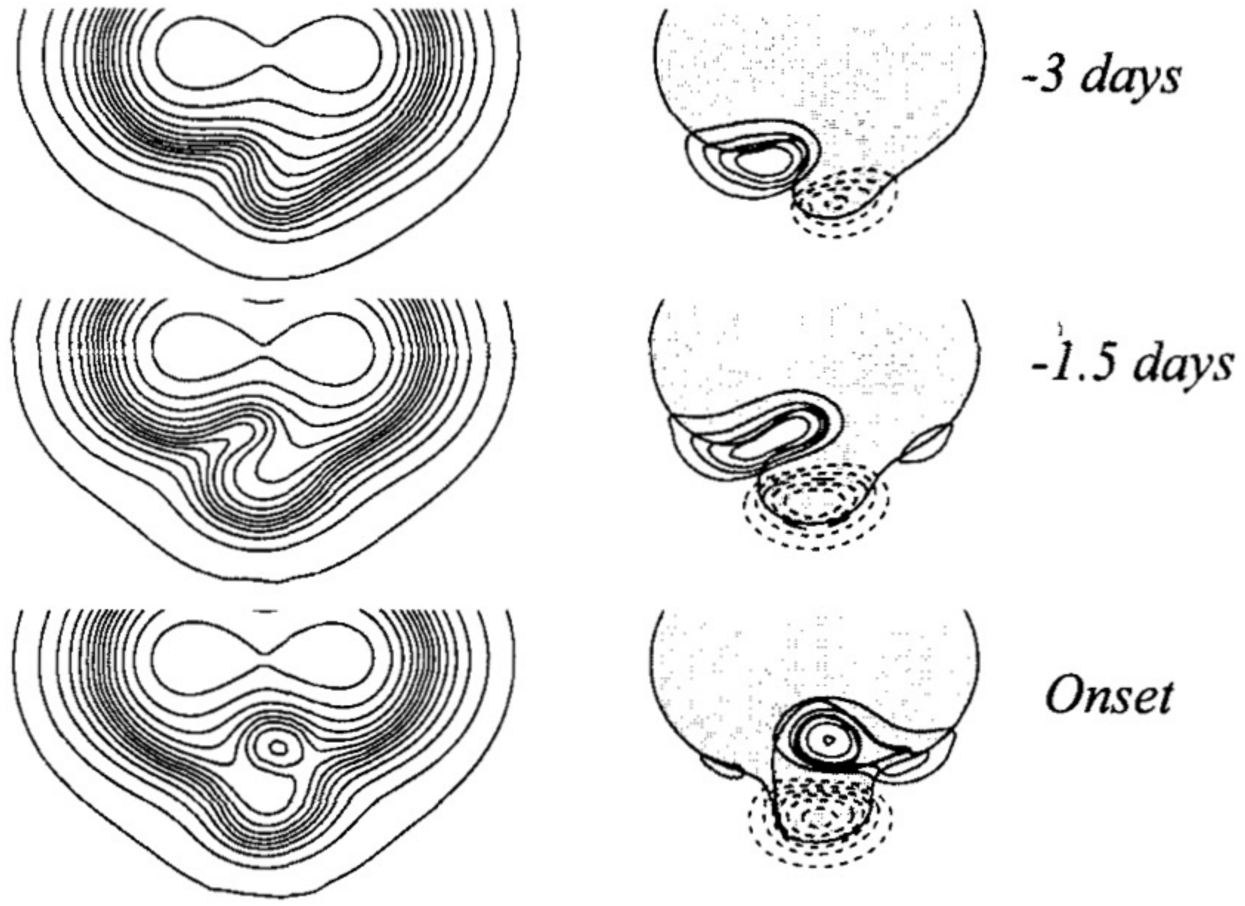
ABSTRACT

A potent mechanism for the generation of low-frequency atmospheric variability on vortex basic states consisting of a single potential vorticity jump, or contour, separating two regions of uniform equivalent barotropic potential vorticity is described. Such basic states represent in a simple manner the potential vorticity distribution of the extratropical upper troposphere. It is shown that the group velocity for stationary waves propagating on such states can vanish for realistic zonal variations in the basic-state flow along the vortex edge, leading to local exponential disturbance growth due to the accumulation of wave action. Further, pseudo-energy stability criteria are derived that suggest that exponentially growing global disturbances are possible for sufficiently strong zonal variations in the flow along the vortex edge.

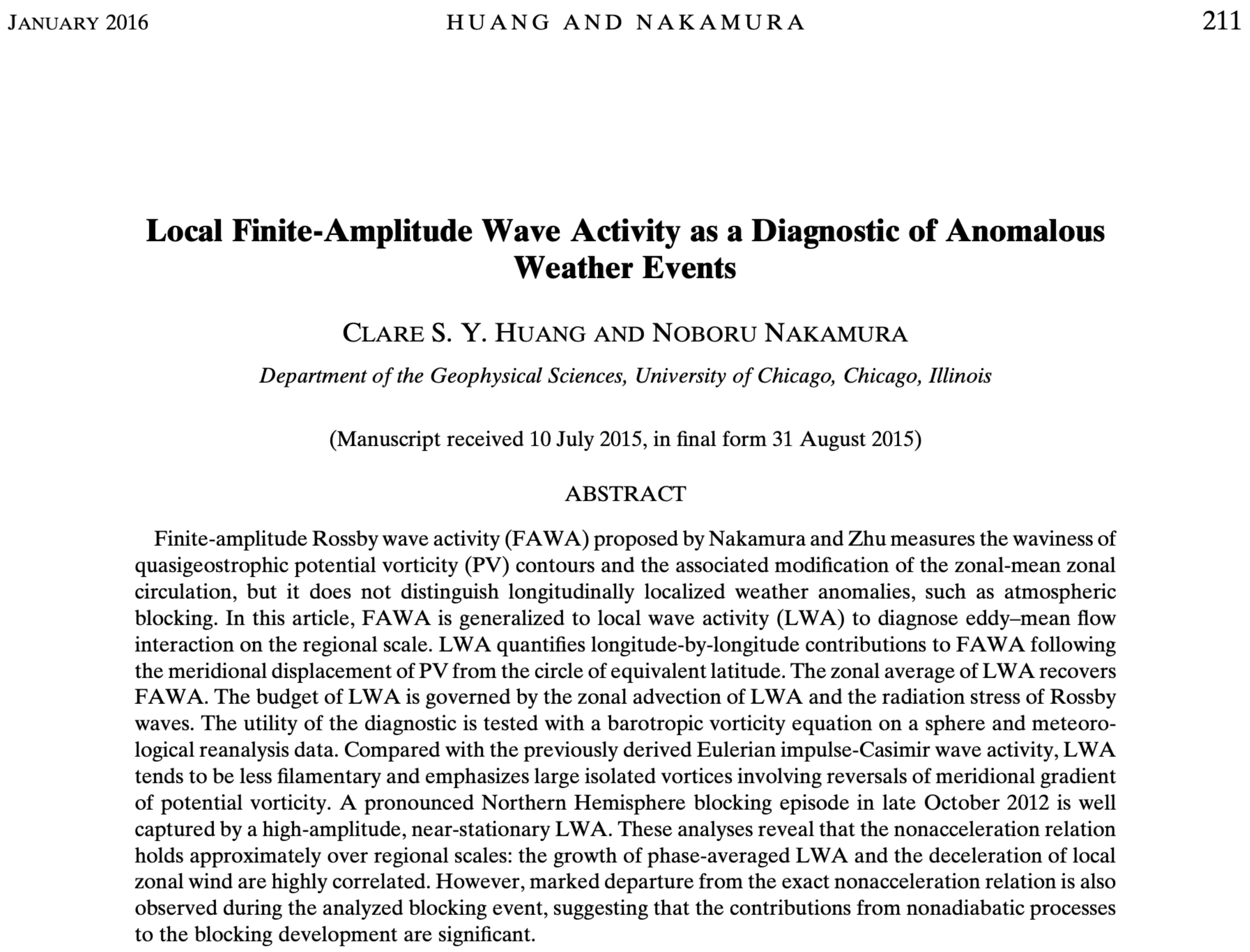
These predictions are examined using linear and nonlinear initial value problem calculations. For wavenumber-1 flow variations in the basic-state zonal flow along the vortex edge, no global instability occurs. However, strong local disturbance growth in response to weak stationary forcing does occur and can lead to irreversible deformation of the vortex. For wavenumber-2 and higher variations in the basic-state zonal flow along the vortex edge, global instability occurs if the stability criteria is violated. These instabilities have peak dimensional *e*-folding times on the order of one week, with faster growth rates corresponding to stronger zonal variations in the flow along the vortex edge. Quantization of the zonal scale of amplifying disturbances occurs, indicating disturbance resonance with the underlying zonal variations in the basic-state flow along the vortex edge. In the nonlinear regime, longer wavelength disturbances lead to large amplitude periodic fluctuations of the vortex. Intermediate wavelength disturbances are shown to yield suprisingly realistic blocking events, while short wavelength disturbances saturate at amplitudes too small to change the overall structure of the vortex.

The pervasiveness of instability in this simple system suggests similar processes may be important for blocking transitions and the generation of low-frequency variability in the extratropical atmosphere. Preliminary results from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis show that the climatological 330-K isentropic potential vorticity is accurately characterized as the time average of a fluctuating single-contour vortex. Wave action conservation on basic states constructed using dynamical fields on the 330-K isentropic surface reproduces observed shifts in low-frequency variability that occur during the El Niño cycle. Further, these shifts lead to transient-driven time mean flow anomalies that have a teleconnection pattern-like structure, despite the fact that meridional propagation of waves is forbidden in this system. The ability of this system to accurately simulate diverse atmospheric phenomena as well as explain certain aspects of upper-tropospheric dynamics suggests that it may provide a powerful new paradigm with which to view low-frequency dynamics in the climate system.

See also Swanson (2001), H. Nakamura (1994)



A wave activity perspective



JANUARY 2016 HUANG AND NAKAMURA 211

Local Finite-Amplitude Wave Activity as a Diagnostic of Anomalous Weather Events

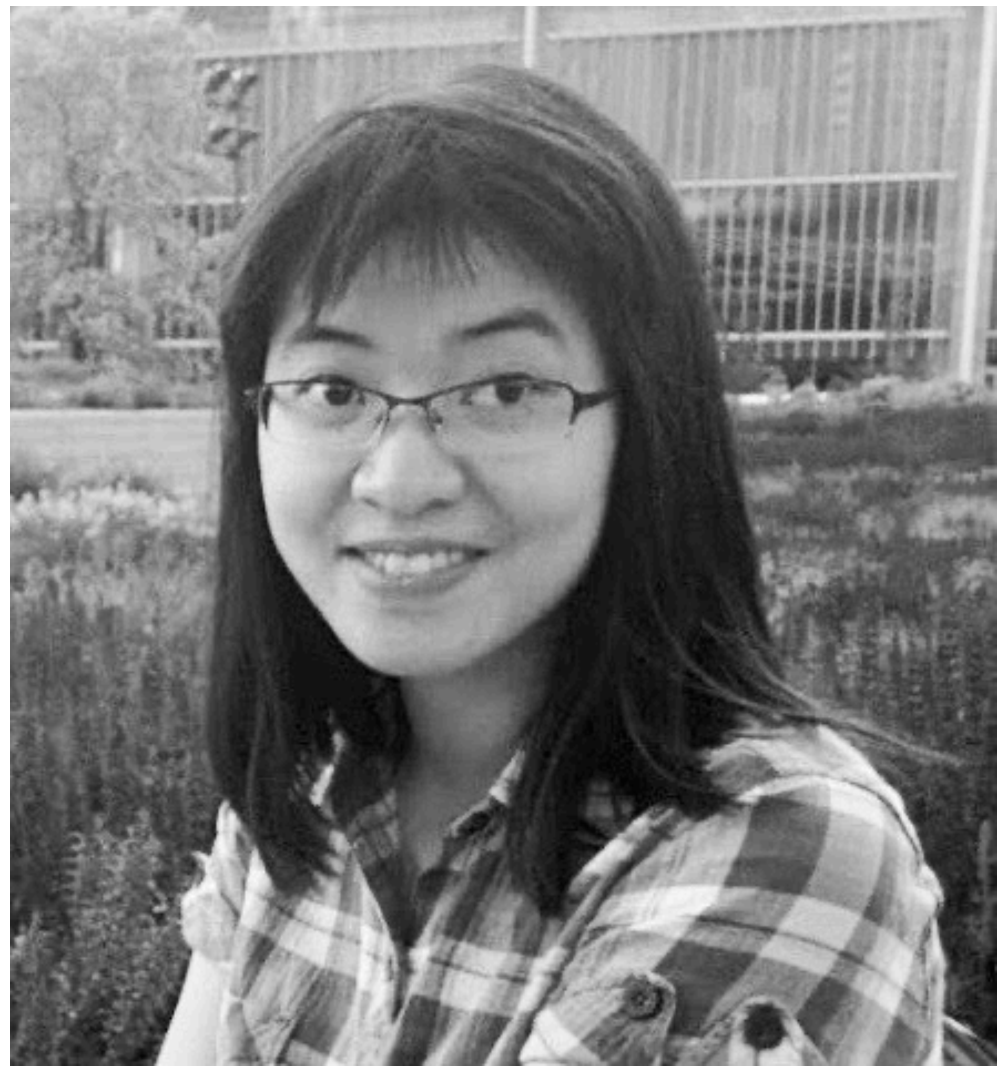
CLARE S. Y. HUANG AND NOBORU NAKAMURA
Department of the Geophysical Sciences, University of Chicago, Chicago, Illinois

(Manuscript received 10 July 2015, in final form 31 August 2015)

ABSTRACT

Finite-amplitude Rossby wave activity (FAWA) proposed by Nakamura and Zhu measures the waviness of quasigeostrophic potential vorticity (PV) contours and the associated modification of the zonal-mean zonal circulation, but it does not distinguish longitudinally localized weather anomalies, such as atmospheric blocking. In this article, FAWA is generalized to local wave activity (LWA) to diagnose eddy–mean flow interaction on the regional scale. LWA quantifies longitude-by-longitude contributions to FAWA following the meridional displacement of PV from the circle of equivalent latitude. The zonal average of LWA recovers FAWA. The budget of LWA is governed by the zonal advection of LWA and the radiation stress of Rossby waves. The utility of the diagnostic is tested with a barotropic vorticity equation on a sphere and meteorological reanalysis data. Compared with the previously derived Eulerian impulse-Casimir wave activity, LWA tends to be less filamentary and emphasizes large isolated vortices involving reversals of meridional gradient of potential vorticity. A pronounced Northern Hemisphere blocking episode in late October 2012 is well captured by a high-amplitude, near-stationary LWA. These analyses reveal that the nonacceleration relation holds approximately over regional scales: the growth of phase-averaged LWA and the deceleration of local zonal wind are highly correlated. However, marked departure from the exact nonacceleration relation is also observed during the analyzed blocking event, suggesting that the contributions from nonadiabatic processes to the blocking development are significant.

See also Chen et al. (2015)



$$A \equiv -\int_0^{\eta(x,y,z,t)} q_e(x,y,y',z,t)\,dy'$$

$$q_e(x,y,y'z,t) = q(x,y+y',z,t) - Q_{\mathrm{REF}}(y,z,t)$$

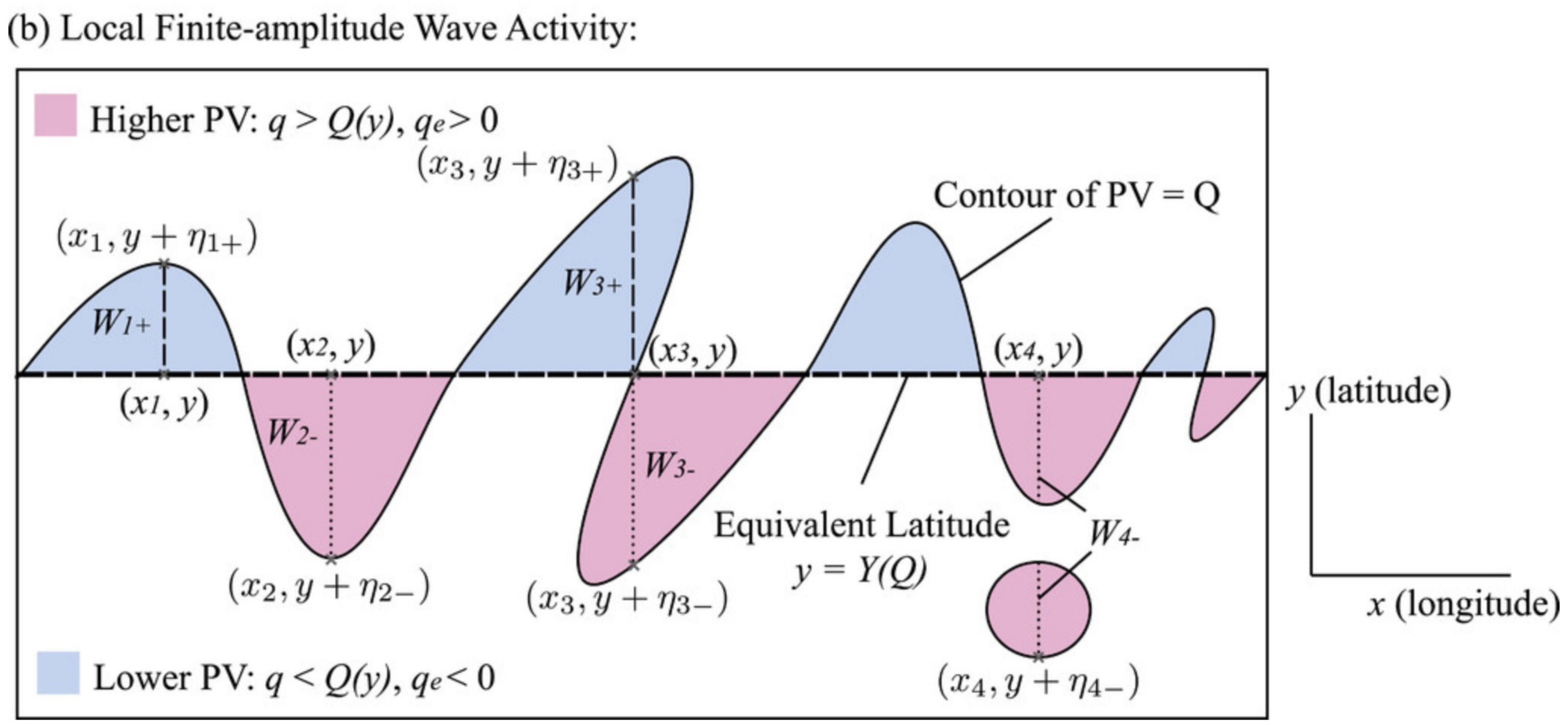
A wave activity perspective

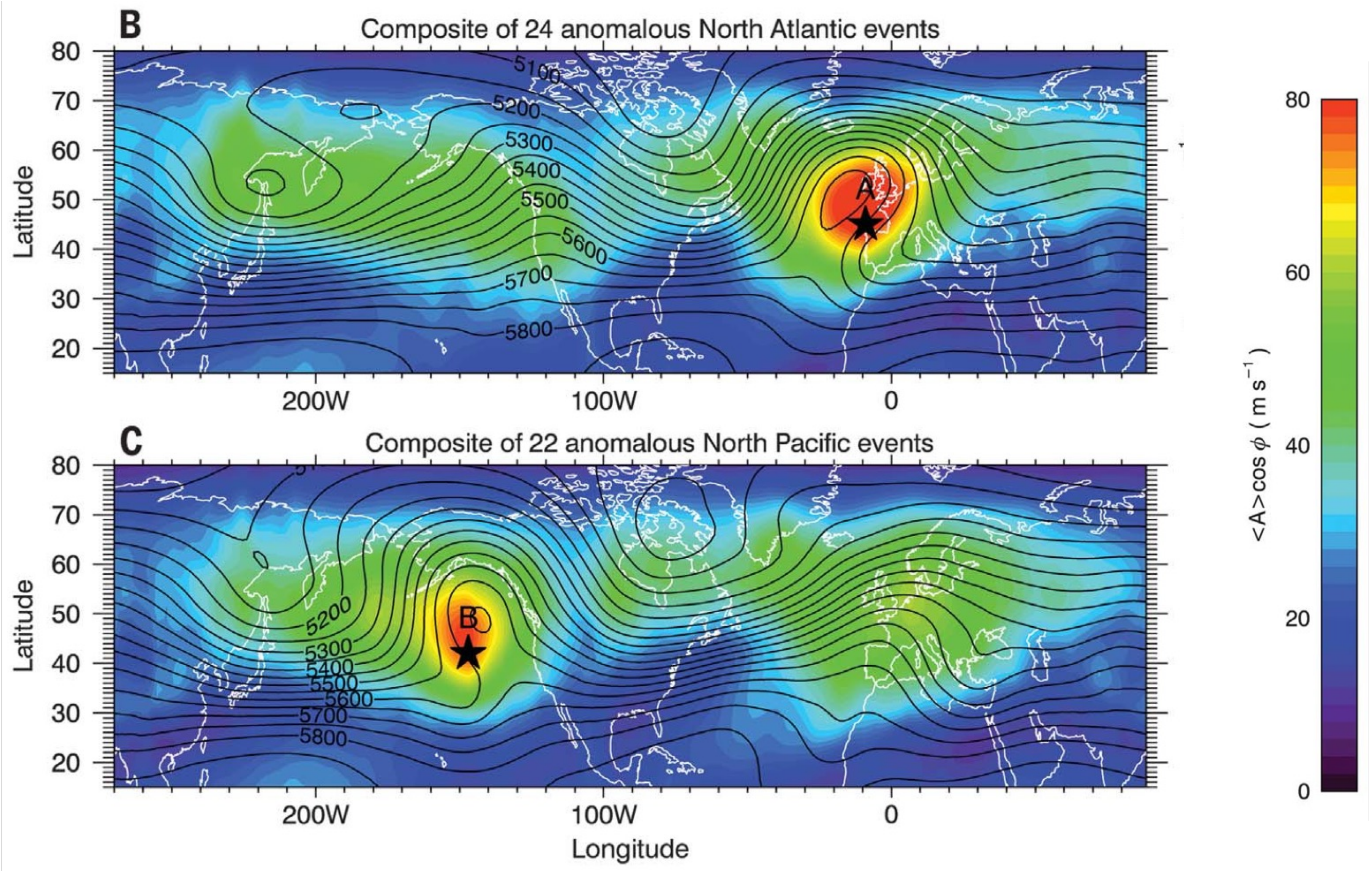
$$A \equiv -\int_0^{\eta(x,y,z,t)} q_e(x,y,y',z,t)dy'$$

$$q_e(x,y,y'z,t) = q(x,y+y',z,t) - Q_{\mathrm{REF}}(y,z,t)$$

Local wave activity: Meridional displacement of QGPV from a zonally symmetric reference state Q_{REF}(y,z,t) (Huang and Nakamura 2016)

Large LWA captures blocking (Nakamura and Huang 2018)


(b) Local Finite-amplitude Wave Activity:



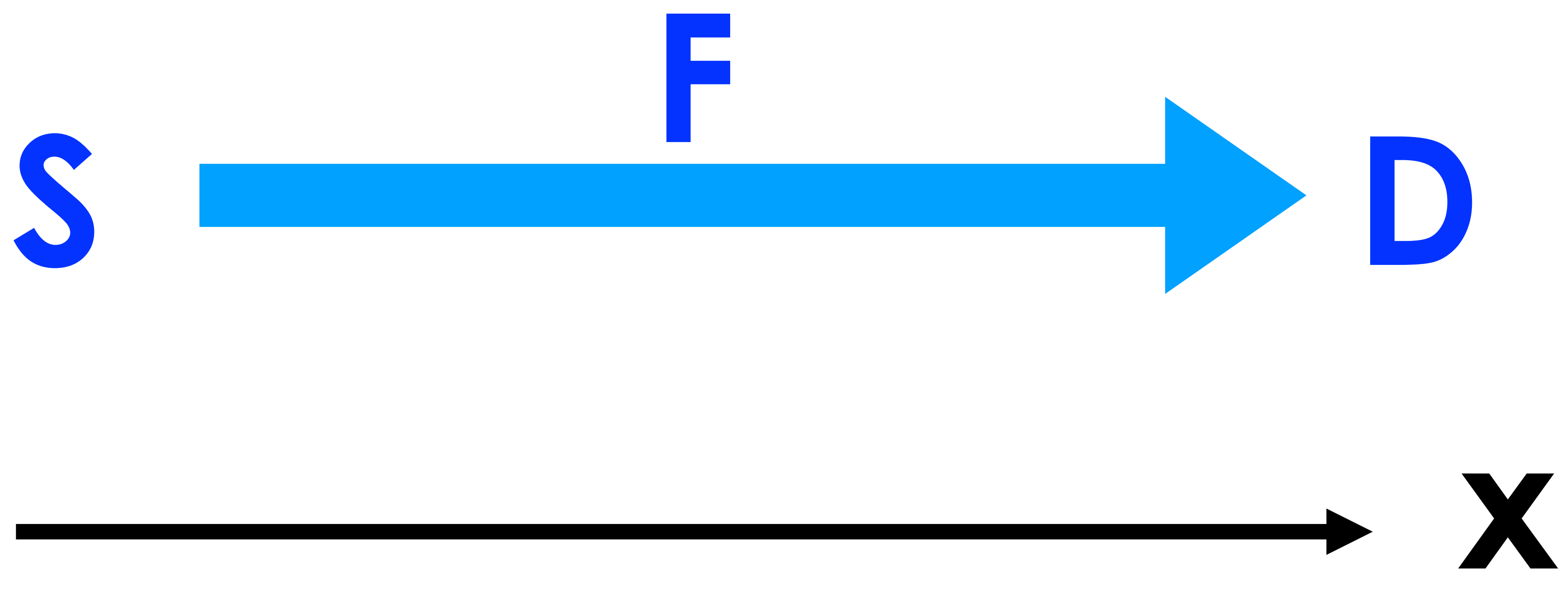
A wave activity perspective

$$\frac{\partial A}{\partial t} = -\nabla \cdot \mathbf{F} + S - D$$

$$\Downarrow$$

$$\frac{\partial A}{\partial t} = -\frac{\partial F}{\partial x} + S - D$$

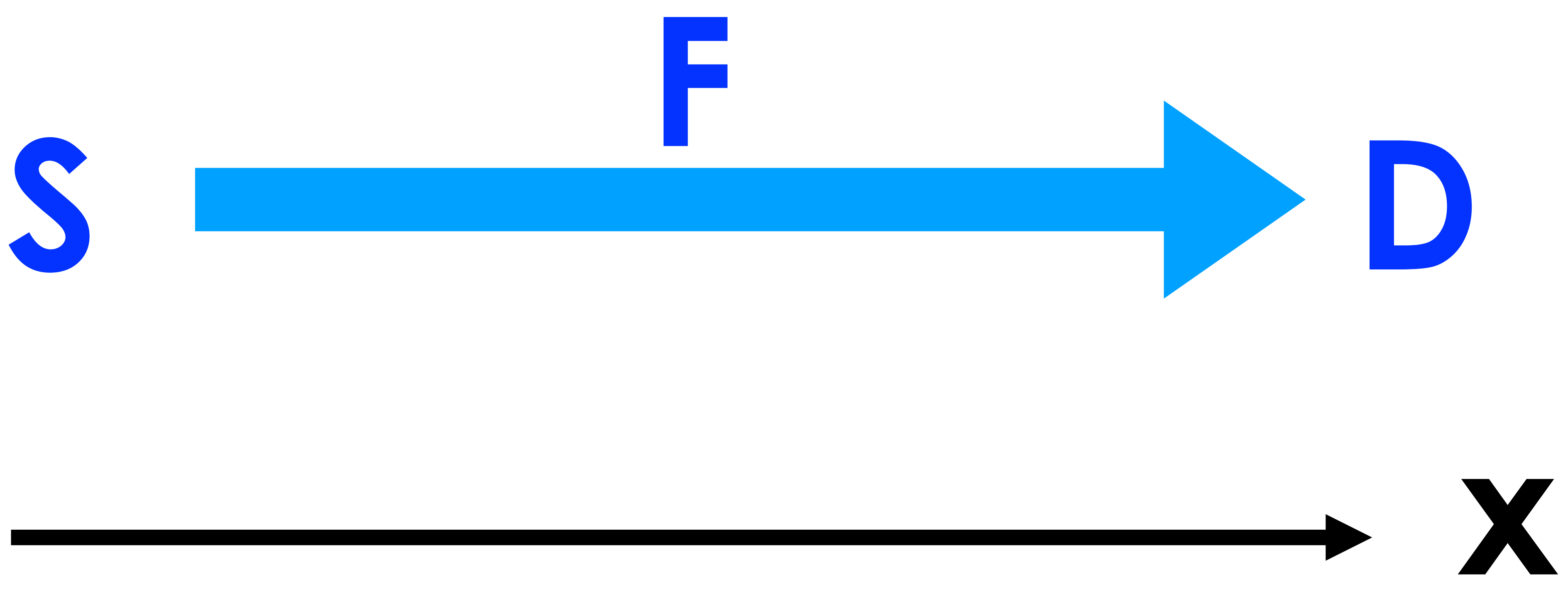
$$A = A(x, t), \quad F = F(A)$$



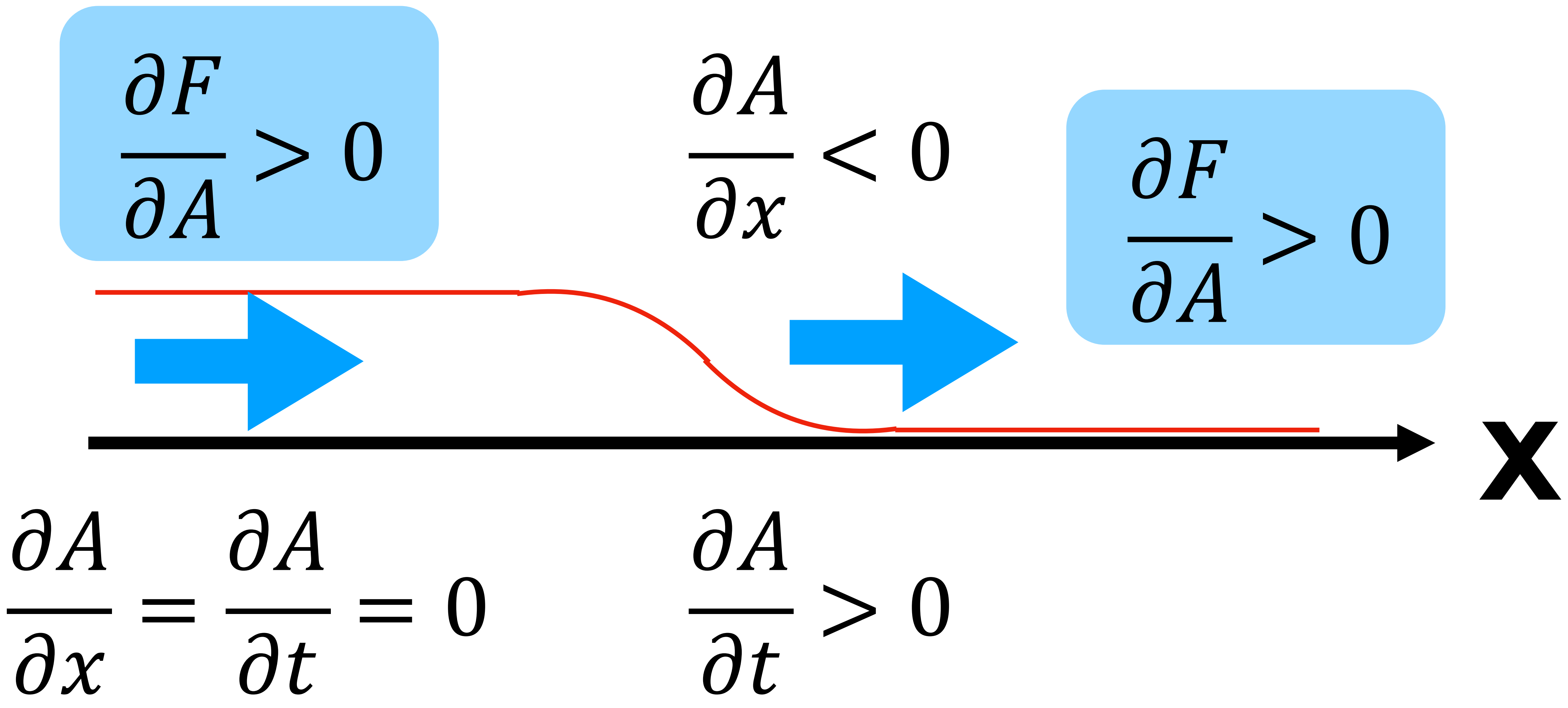
A wave activity perspective

$$\frac{\partial A}{\partial t} = -\frac{\partial F}{\partial x} = -\frac{\partial F}{\partial A}\frac{\partial A}{\partial x}$$

$\frac{\partial F}{\partial A}$: Effective "advective" velocity



"Transmission"



$$\frac{\partial F}{\partial A} > 0$$

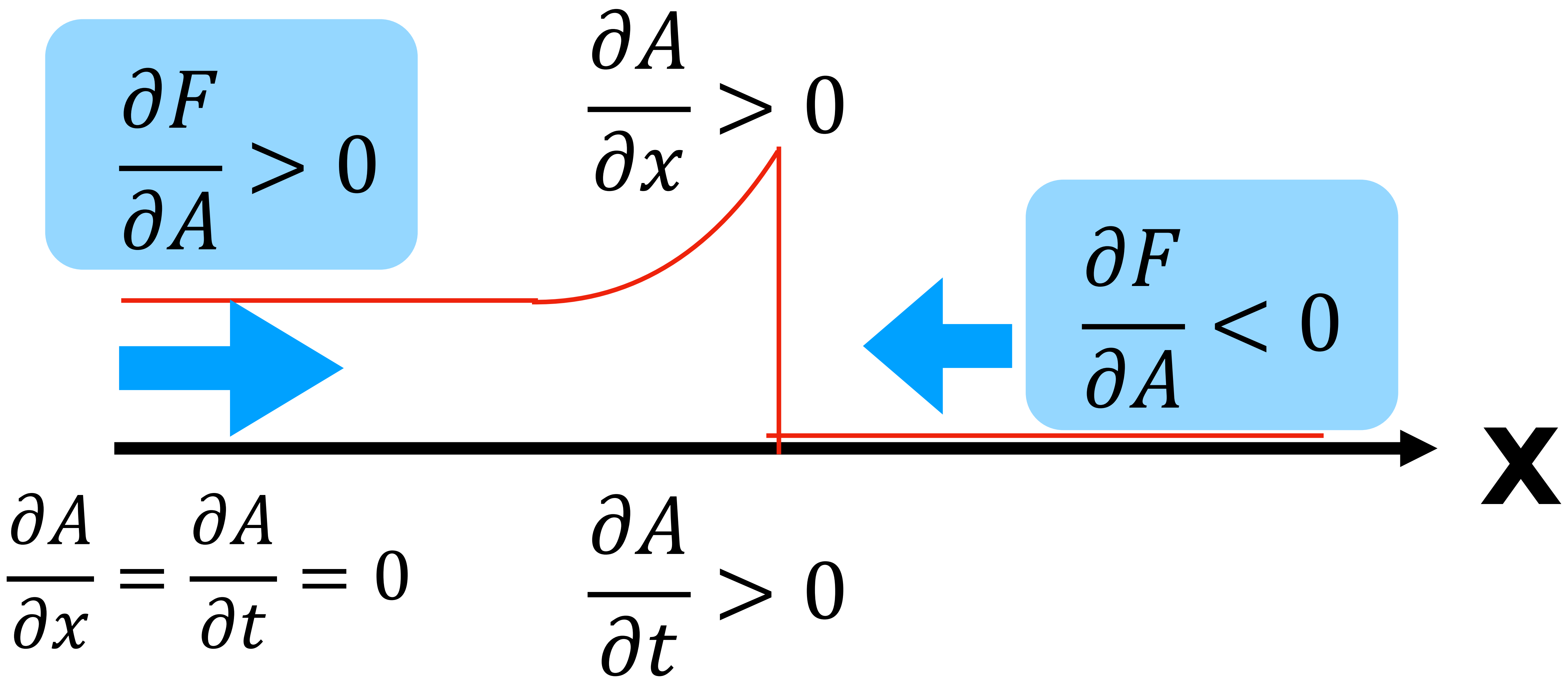
$$\frac{\partial A}{\partial x} < 0$$

$$\frac{\partial F}{\partial A} > 0$$

$$\frac{\partial A}{\partial x} = \frac{\partial A}{\partial t} = 0$$

$$\frac{\partial A}{\partial t} > 0$$

"Stagnation (unstable)"



$$\frac{\partial F}{\partial A} > 0$$

$$\frac{\partial A}{\partial x} > 0$$

$$\frac{\partial F}{\partial A} < 0$$

$$\frac{\partial A}{\partial x} = \frac{\partial A}{\partial t} = 0$$

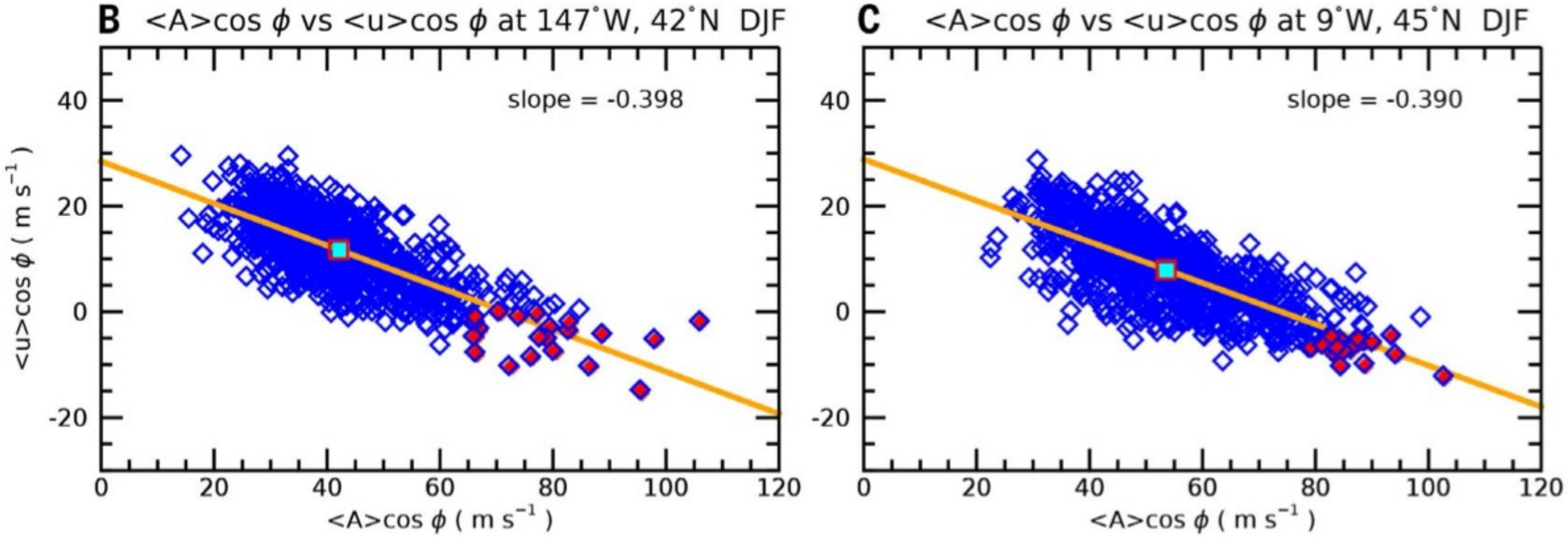
$$\frac{\partial A}{\partial t} > 0$$

A wave activity perspective

$$F = (\, u + c_g^x \,)\, A \approx (\, u_0 - \alpha A + c_g^x \,)\, A$$

$$u \approx u_0 - \alpha A, \quad 0 < \alpha \leq 1$$

“Eddy-flow interaction”



Nakamura and Huang (2018)

A wave activity perspective

$$F = (\,u + c_g^x\,)\,A \approx (\,u_0 - \alpha A + c_g^x\,)\,A$$

$$u \approx u_0 - \alpha A, \quad 0 < \alpha \leq 1$$

$$A(x,t) \equiv A_0(x) + \hat{A}(x,t)$$

Stationary **Transient**

$$\frac{\partial \hat{A}}{\partial t} = -\frac{\partial \hat{F}}{\partial x} + \hat{S} - \hat{D}$$

$$\hat{F} = [C(x) - \alpha \hat{A}]\,\hat{A}, \quad C(x) = u_0 + c_g^x - 2\alpha A_0(x)$$

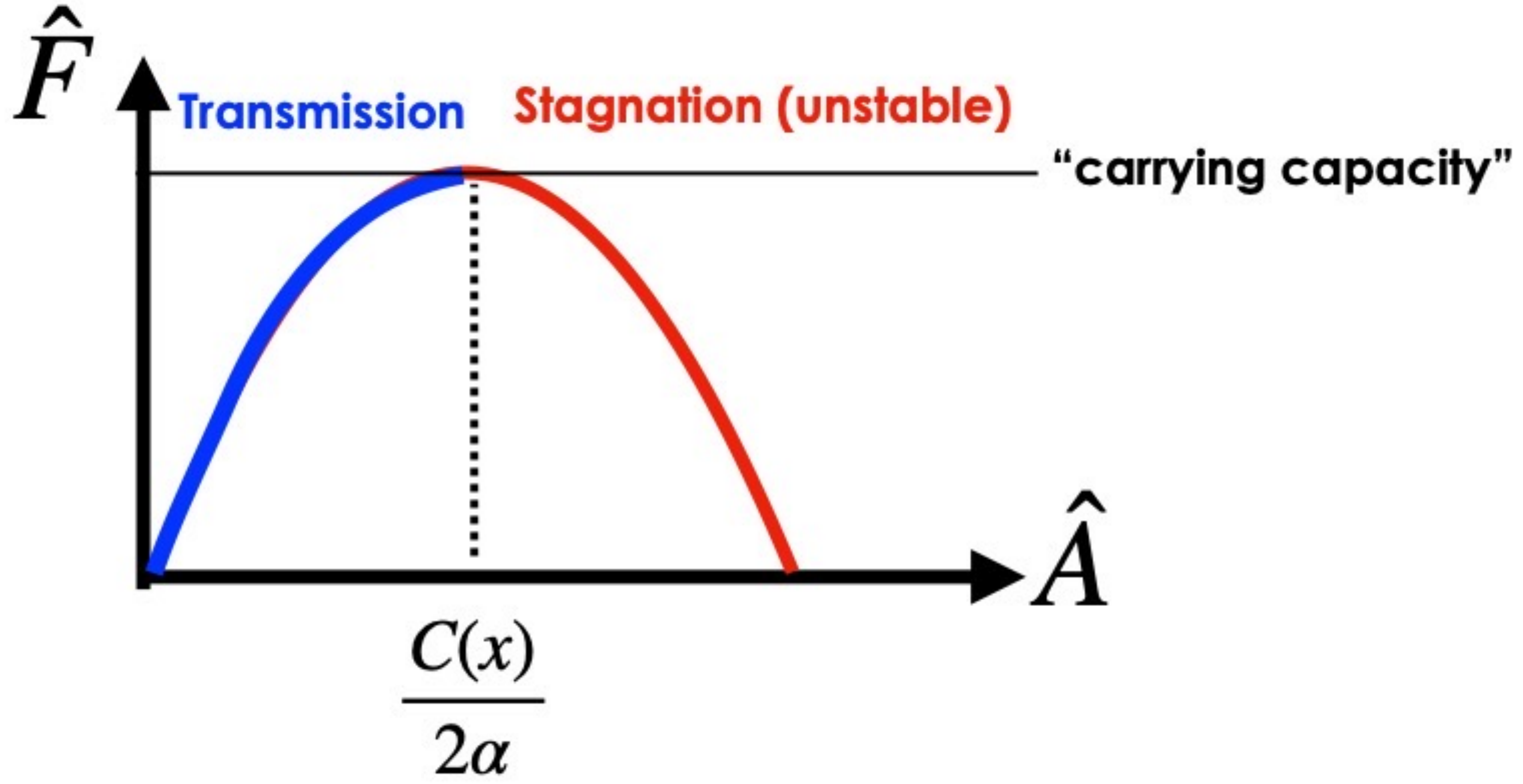
A wave activity perspective

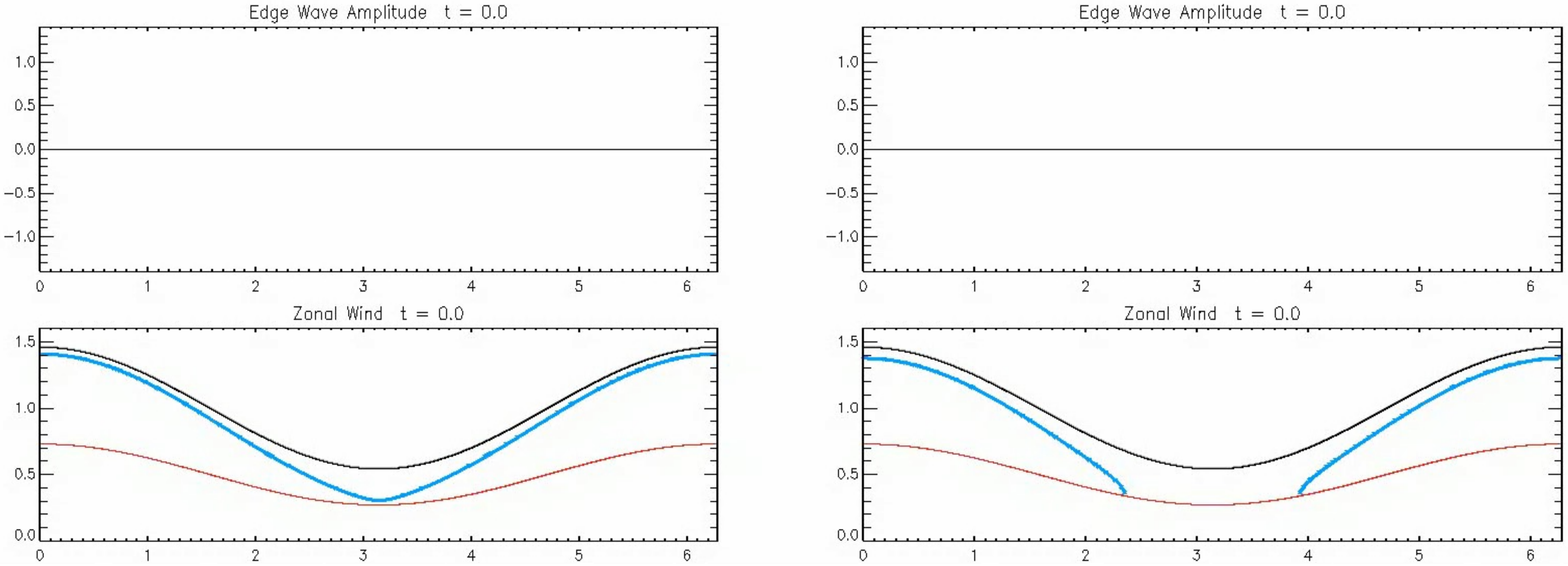
$$\frac{\partial \hat{A}}{\partial t} = -\frac{\partial \hat{F}}{\partial x} + \hat{S} - \hat{D}$$

$$\hat{F} = [C(x) - \alpha \hat{A}]\, \hat{A}, \quad C(x) = u_0 + c_g^x - 2\alpha A_0(x)$$

Effective advective velocity

$$\frac{\partial \hat{F}}{\partial \hat{A}} = C(x) - 2\alpha \hat{A} \begin{cases} > 0, & \hat{A} < \frac{C(x)}{2\alpha} \\ \leq 0, & \hat{A} \geq \frac{C(x)}{2\alpha} \end{cases}$$

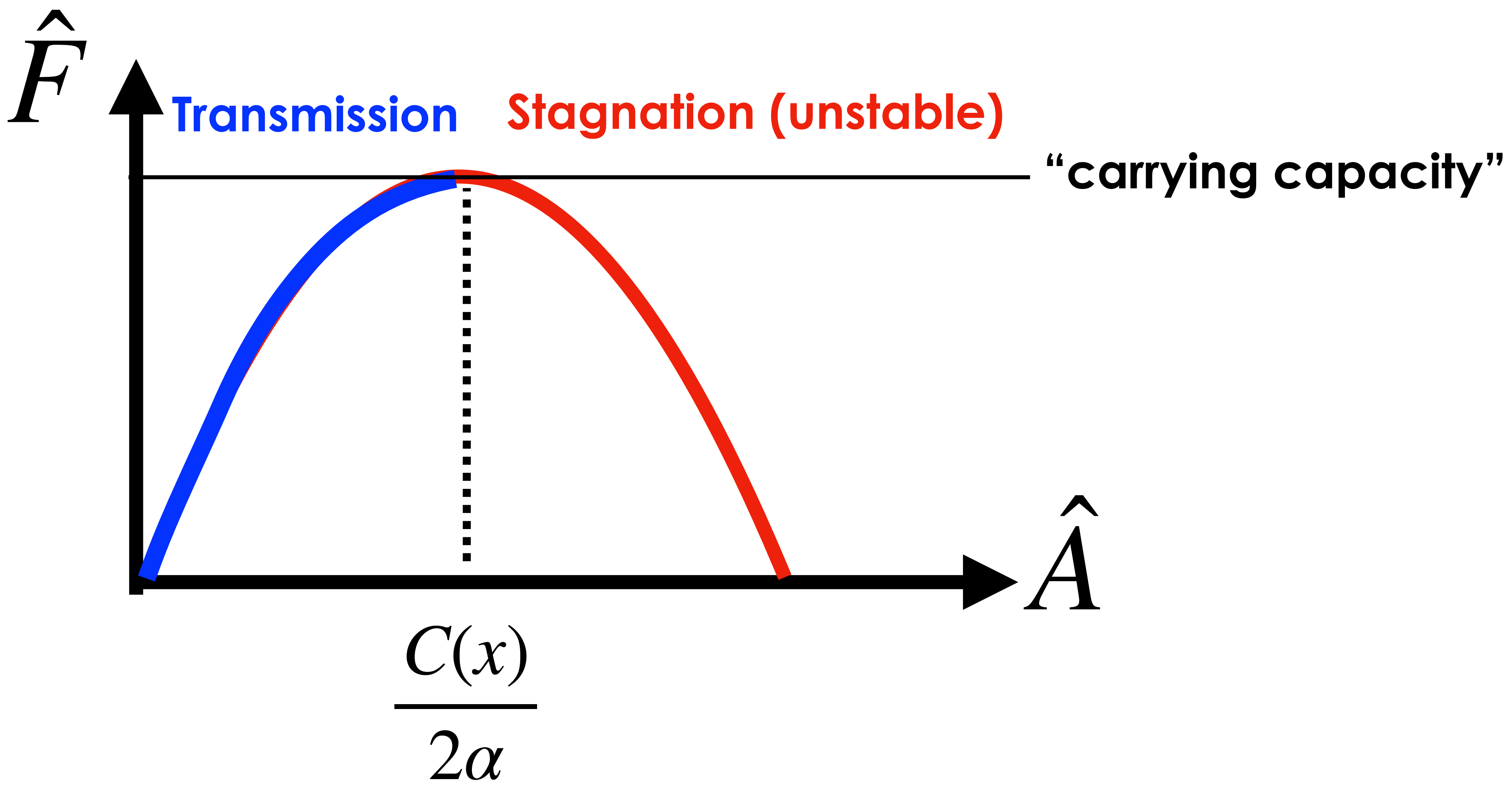


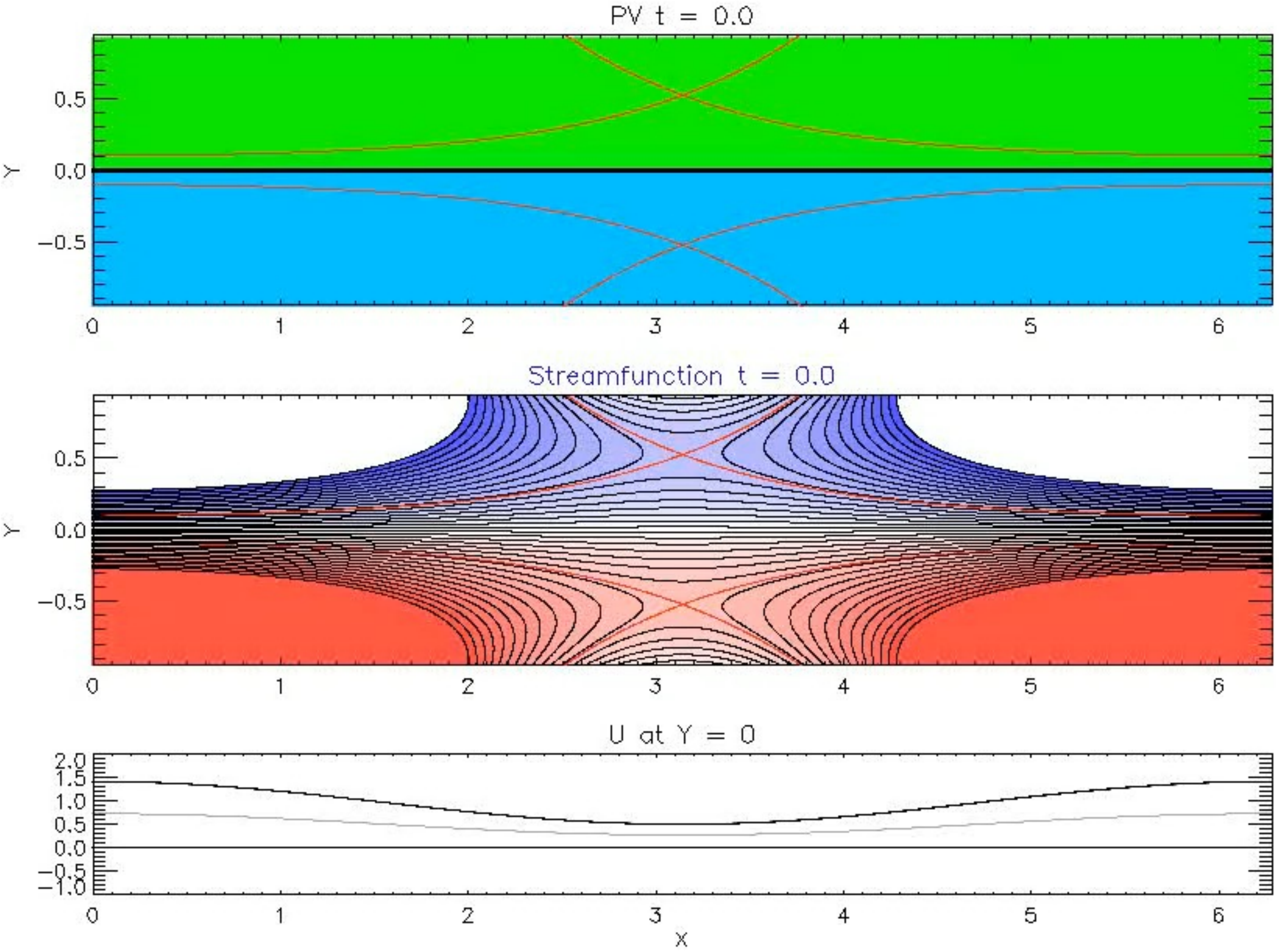


Nakamura and Huang (2017)

Effective advective velocity

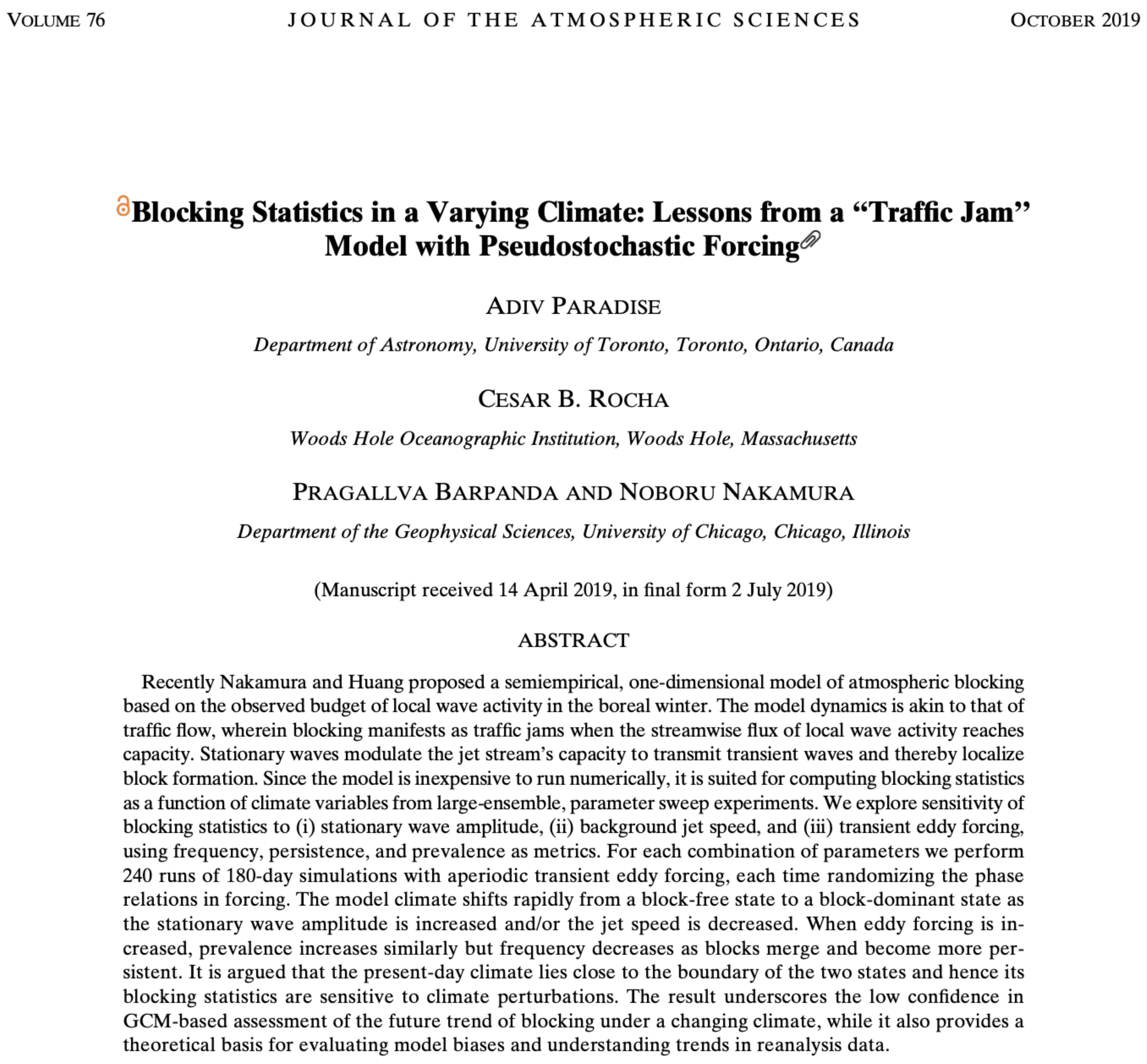
$$\frac{\partial \hat{F}}{\partial \hat{A}} = C(x) - 2\alpha\hat{A} \begin{cases} > 0, & \hat{A} < \dfrac{C(x)}{2\alpha} \\ \leq 0, & \hat{A} \geq \dfrac{C(x)}{2\alpha} \end{cases}$$





Nakamura and Huang (2017)

Connection to “climate change”



VOLUME 76 JOURNAL OF THE ATMOSPHERIC SCIENCES OCTOBER 2019

Blocking Statistics in a Varying Climate: Lessons from a “Traffic Jam” Model with Pseudostochastic Forcing

ADIV PARADISE

Department of Astronomy, University of Toronto, Toronto, Ontario, Canada

CESAR B. ROCHA

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

PRAGALLVA BARPANDA AND NOBORU NAKAMURA

Department of the Geophysical Sciences, University of Chicago, Chicago, Illinois

(Manuscript received 14 April 2019, in final form 2 July 2019)

ABSTRACT

Recently Nakamura and Huang proposed a semiempirical, one-dimensional model of atmospheric blocking based on the observed budget of local wave activity in the boreal winter. The model dynamics is akin to that of traffic flow, wherein blocking manifests as traffic jams when the streamwise flux of local wave activity reaches capacity. Stationary waves modulate the jet stream’s capacity to transmit transient waves and thereby localize block formation. Since the model is inexpensive to run numerically, it is suited for computing blocking statistics as a function of climate variables from large-ensemble, parameter sweep experiments. We explore sensitivity of blocking statistics to (i) stationary wave amplitude, (ii) background jet speed, and (iii) transient eddy forcing, using frequency, persistence, and prevalence as metrics. For each combination of parameters we perform 240 runs of 180-day simulations with aperiodic transient eddy forcing, each time randomizing the phase relations in forcing. The model climate shifts rapidly from a block-free state to a block-dominant state as the stationary wave amplitude is increased and/or the jet speed is decreased. When eddy forcing is increased, prevalence increases similarly but frequency decreases as blocks merge and become more persistent. It is argued that the present-day climate lies close to the boundary of the two states and hence its blocking statistics are sensitive to climate perturbations. The result underscores the low confidence in GCM-based assessment of the future trend of blocking under a changing climate, while it also provides a theoretical basis for evaluating model biases and understanding trends in reanalysis data.

See also Valva and Nakamura (2021)

OCTOBER 2019 PARADISE ET AL. 3023

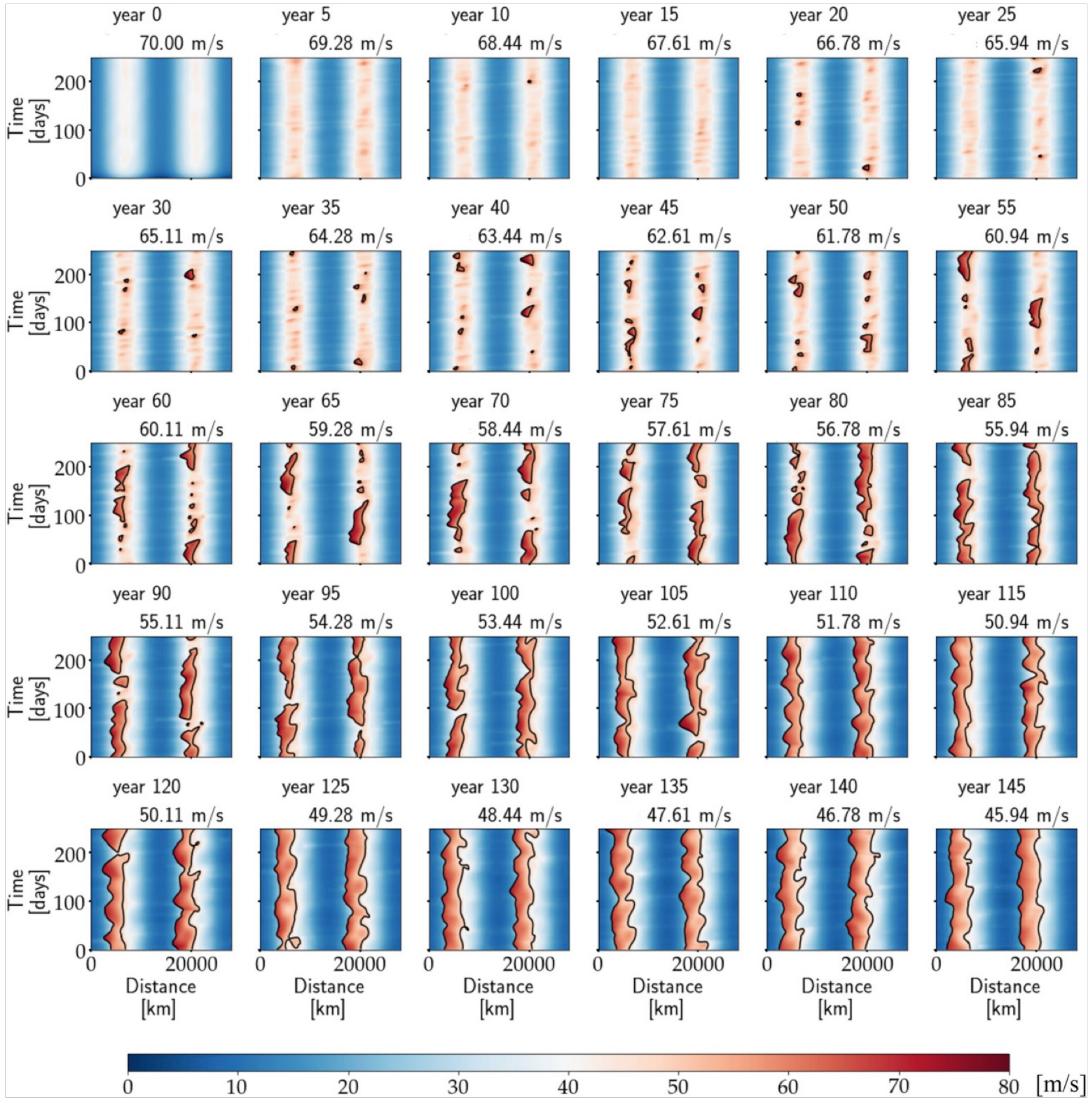
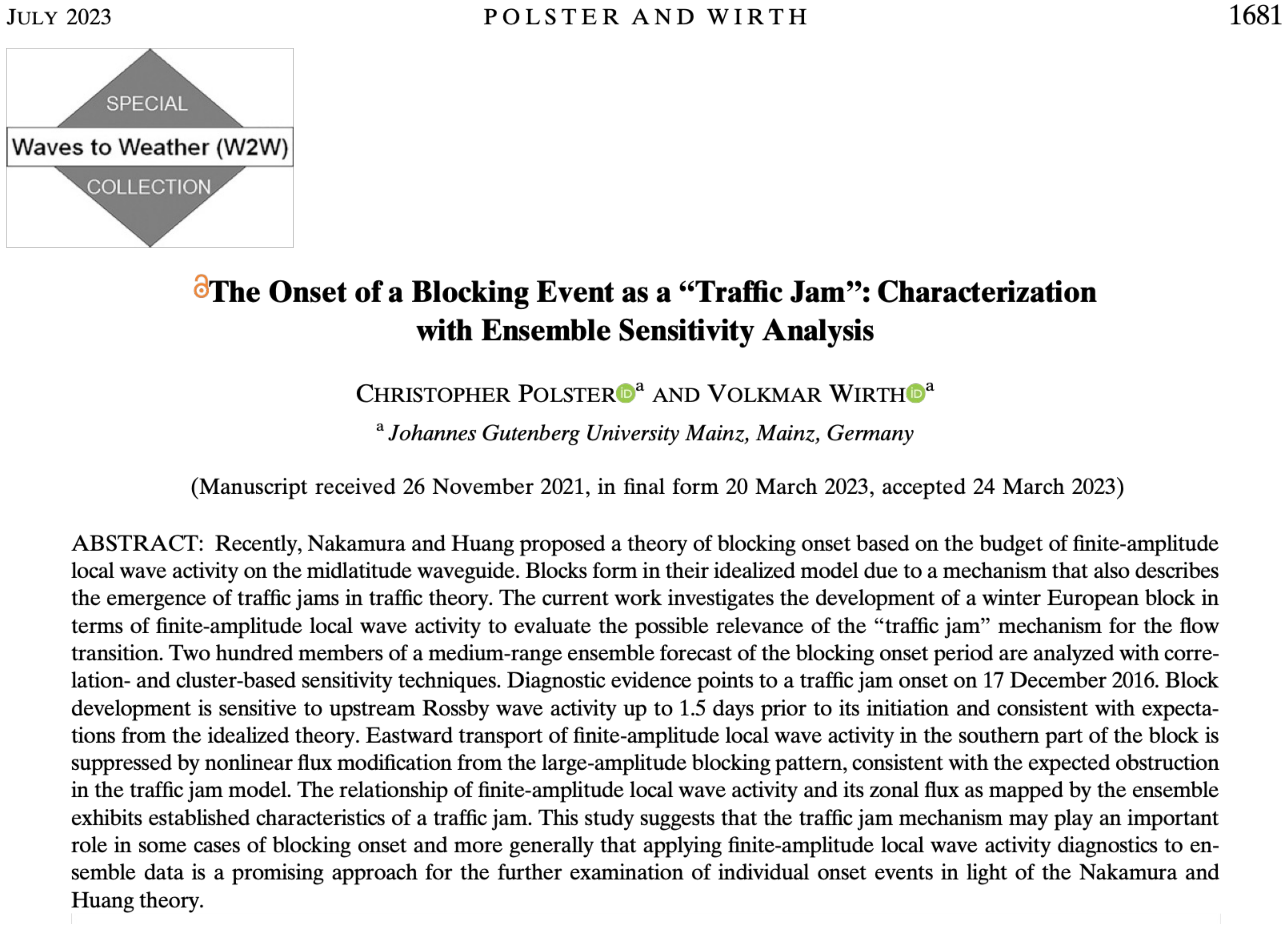


FIG. 6. Total wave activity in a long-term simulation (from year 0 to 145), in which U_J is decreased from 70 m s^{-1} at a rate of 0.17 m s^{-1} yr^{-1}, while we fix $2\alpha\Lambda = 11$ m s^{-1}, $\gamma = 2$, $k = 2$, and $\varepsilon = 0.5$. Each panel shows 250 days of snapshots 5 years apart. The value of U_J averaged over the 250-day period is shown above each panel. The transient eddy forcing is introduced after year 0 and is not reflected in the top-left panel. Other conventions are as in Figs. 2a and 2e. See text for details.

A case study (Dec 2016 N Atlantic)



SPECIAL
Waves to Weather (W2W)
COLLECTION

The Onset of a Blocking Event as a "Traffic Jam": Characterization with Ensemble Sensitivity Analysis

CHRISTOPHER POLSTER[a] AND VOLKMAR WIRTH[a]
[a] *Johannes Gutenberg University Mainz, Mainz, Germany*

(Manuscript received 26 November 2021, in final form 20 March 2023, accepted 24 March 2023)

ABSTRACT: Recently, Nakamura and Huang proposed a theory of blocking onset based on the budget of finite-amplitude local wave activity on the midlatitude waveguide. Blocks form in their idealized model due to a mechanism that also describes the emergence of traffic jams in traffic theory. The current work investigates the development of a winter European block in terms of finite-amplitude local wave activity to evaluate the possible relevance of the "traffic jam" mechanism for the flow transition. Two hundred members of a medium-range ensemble forecast of the blocking onset period are analyzed with correlation- and cluster-based sensitivity techniques. Diagnostic evidence points to a traffic jam onset on 17 December 2016. Block development is sensitive to upstream Rossby wave activity up to 1.5 days prior to its initiation and consistent with expectations from the idealized theory. Eastward transport of finite-amplitude local wave activity in the southern part of the block is suppressed by nonlinear flux modification from the large-amplitude blocking pattern, consistent with the expected obstruction in the traffic jam model. The relationship of finite-amplitude local wave activity and its zonal flux as mapped by the ensemble exhibits established characteristics of a traffic jam. This study suggests that the traffic jam mechanism may play an important role in some cases of blocking onset and more generally that applying finite-amplitude local wave activity diagnostics to ensemble data is a promising approach for the further examination of individual onset events in light of the Nakamura and Huang theory.

- Vast majority of ensemble members underestimate the event

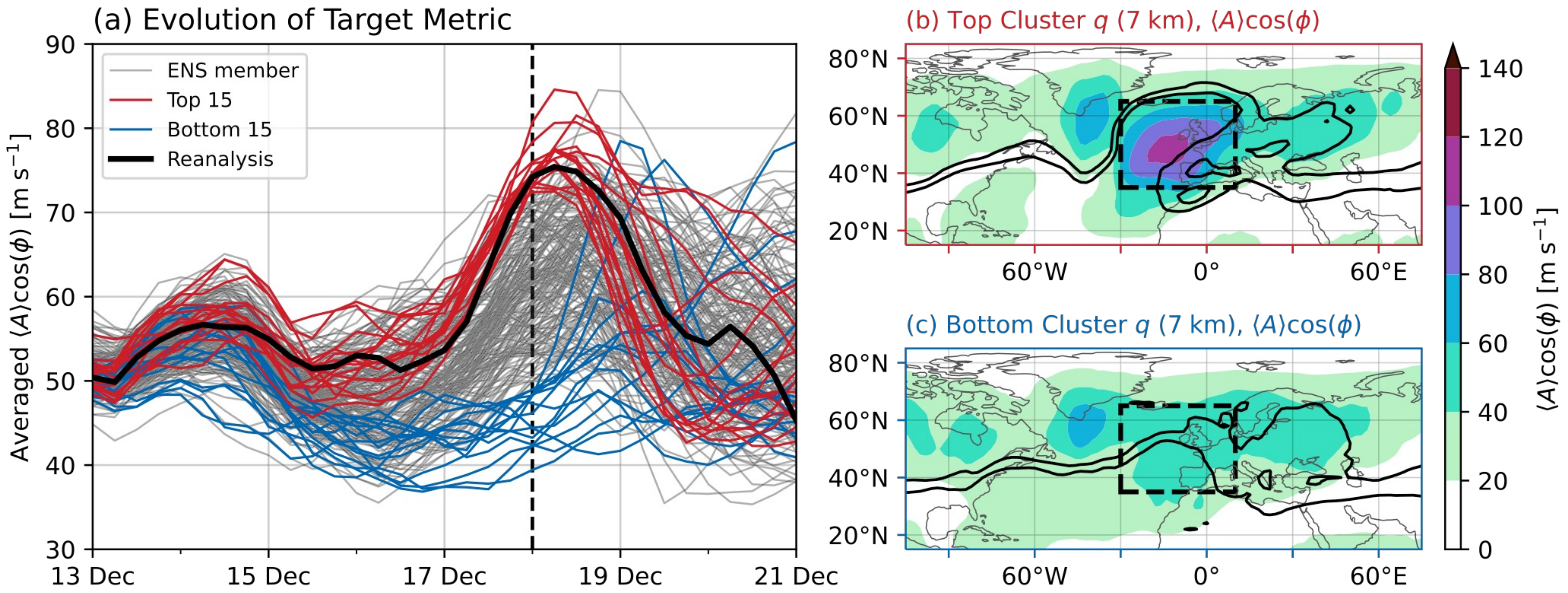
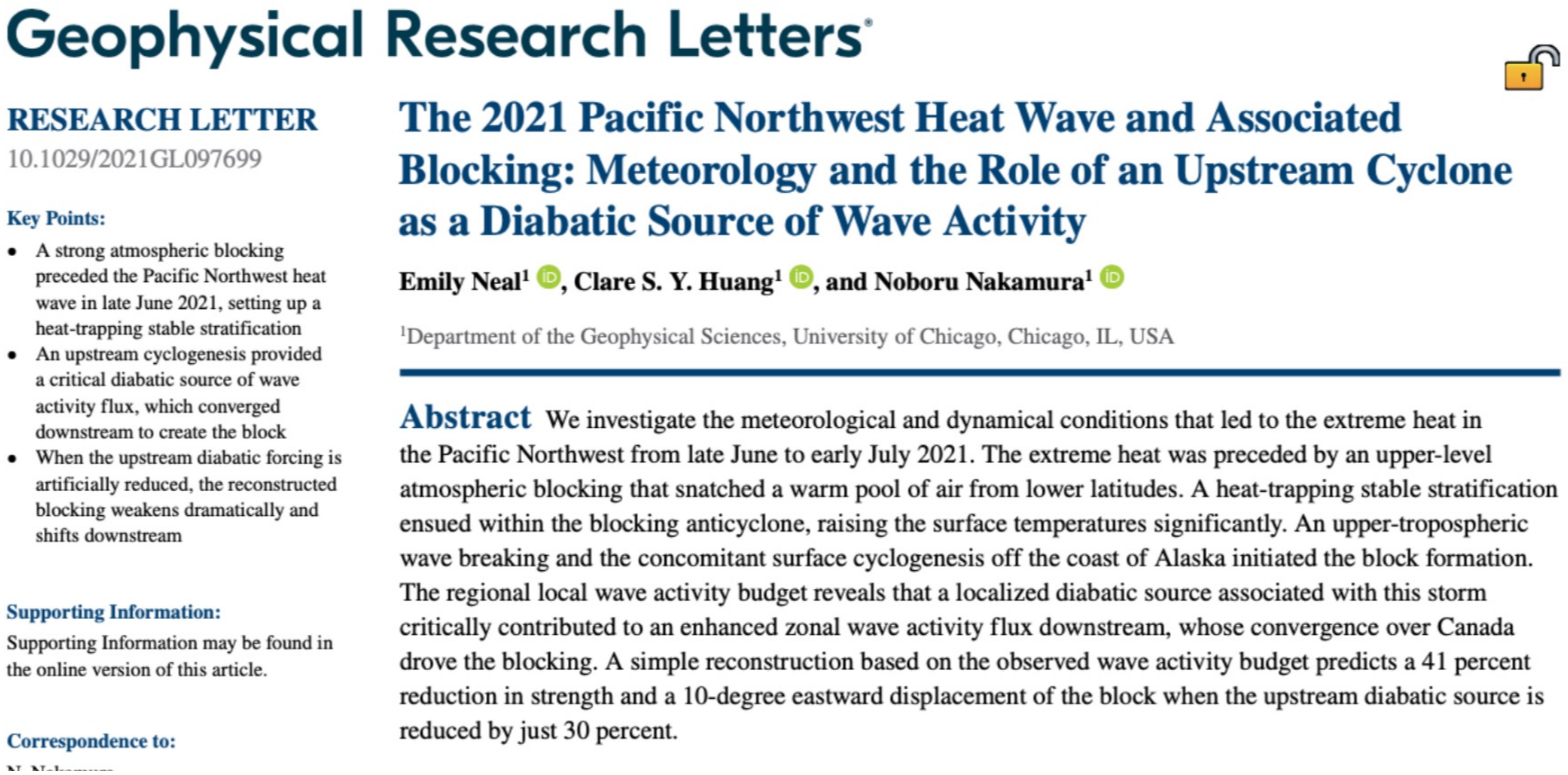


FIG. 3. (a) Time series of the target metric (used to quantify the strength of the blocked flow pattern) in the sensitivity analysis time period (see Fig. 1), evaluated with data from reanalysis (bold black line) and all members of the forecast ensemble (gray, red, and blue lines). The vertical dashed line indicates the target evaluation time. The red- and blue-colored lines highlight the 15 top- and bottom-ranking ensemble members in the distribution of the target metric at the target evaluation time, respectively. (b),(c) Mean fields of PV at 7-km height (contours, as in Fig. 2a) and LWA (shading) of the 15 top- and bottom-ranking ensemble members, respectively, at 0000 UTC 18 Dec 2016. The contour levels, color bar, and target evaluation region box (dashed) are identical to that of Fig. 2a.

Connection to extreme heat



Geophysical Research Letters

RESEARCH LETTER

10.1029/2021GL097699

Key Points:

- A strong atmospheric blocking preceded the Pacific Northwest heat wave in late June 2021, setting up a heat-trapping stable stratification
- An upstream cyclogenesis provided a critical diabatic source of wave activity flux, which converged downstream to create the block
- When the upstream diabatic forcing is artificially reduced, the reconstructed blocking weakens dramatically and shifts downstream

Supporting Information:

Supporting Information may be found in the online version of this article.

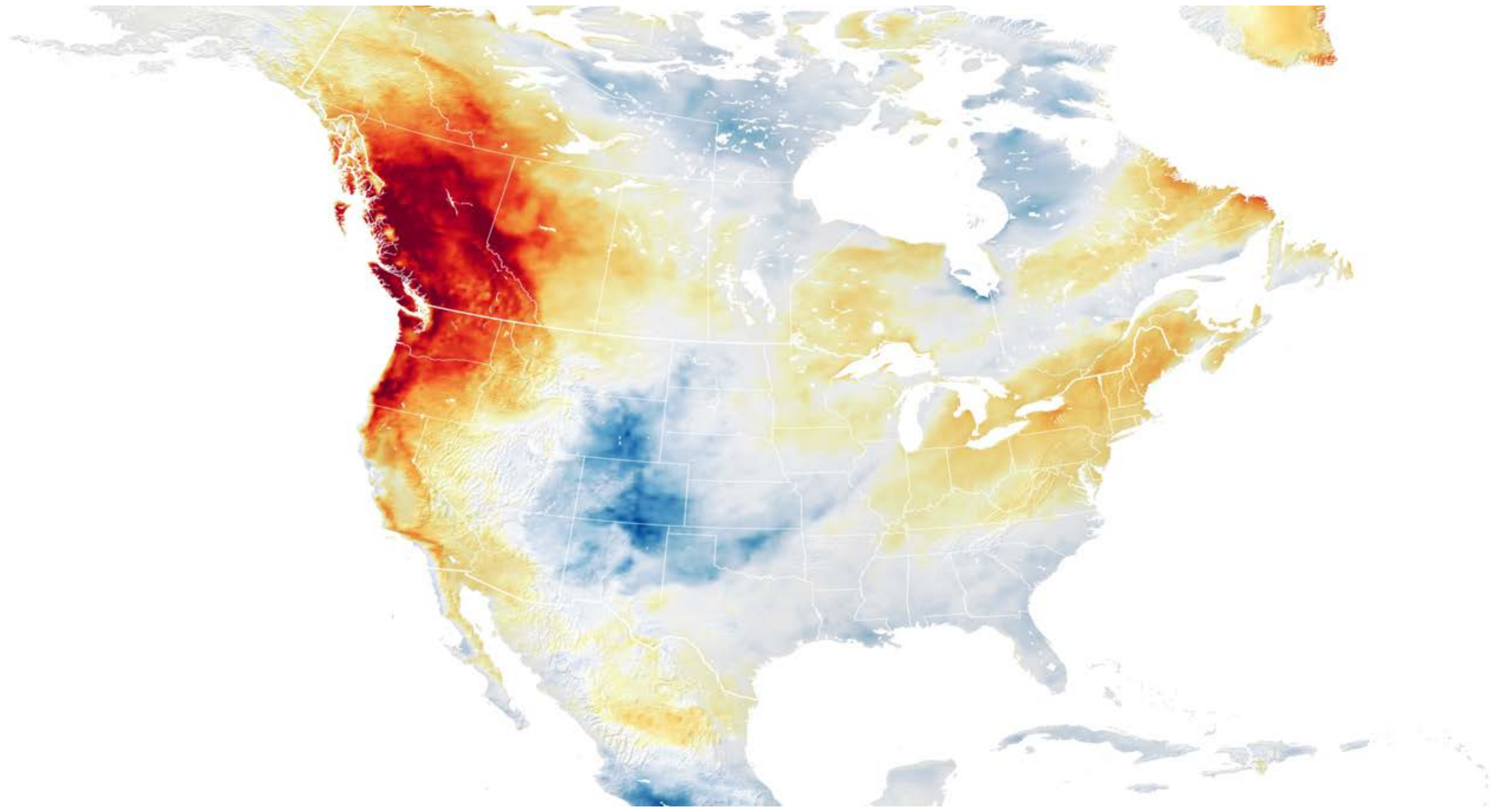
Correspondence to:

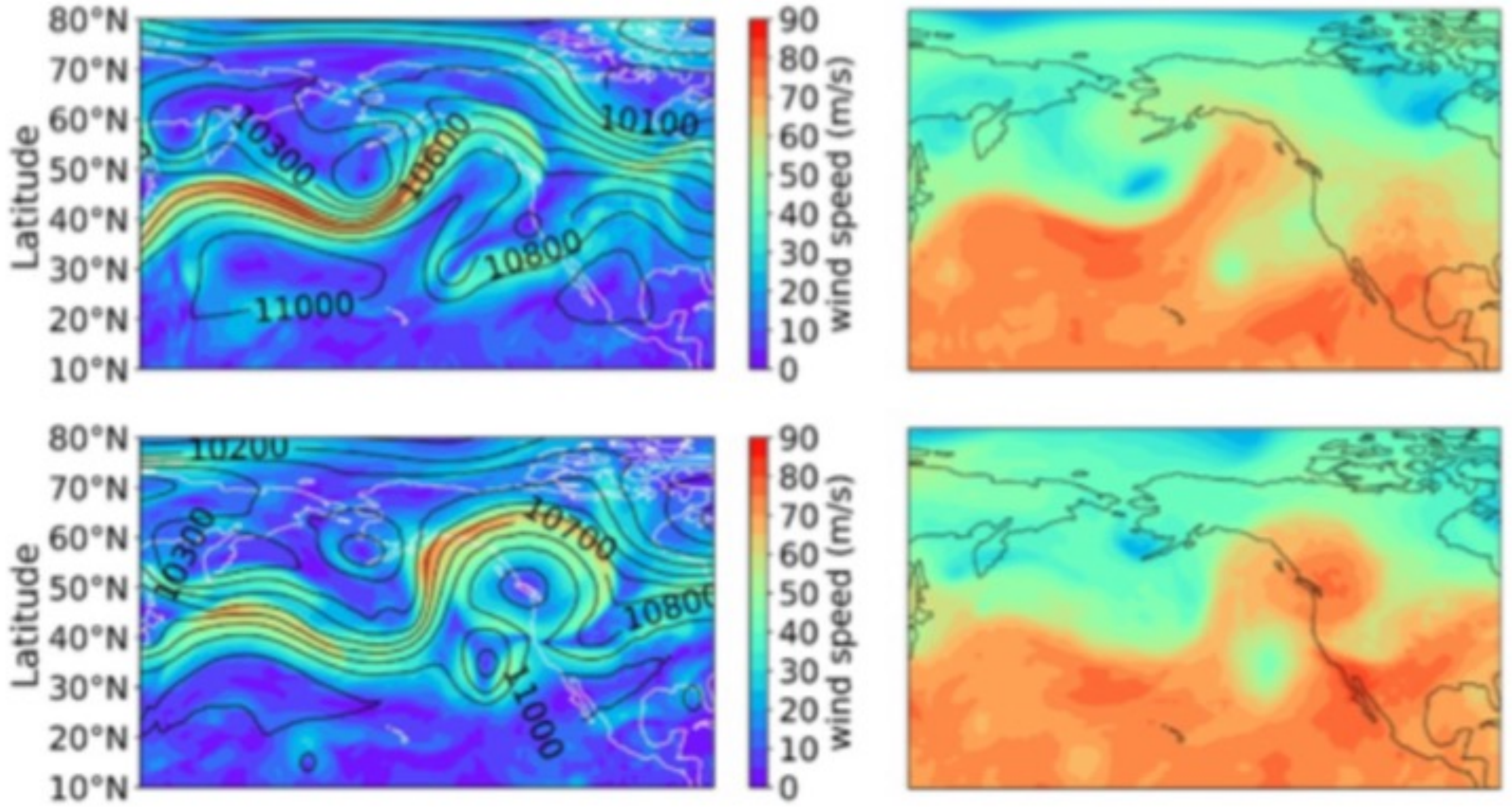
The 2021 Pacific Northwest Heat Wave and Associated Blocking: Meteorology and the Role of an Upstream Cyclone as a Diabatic Source of Wave Activity

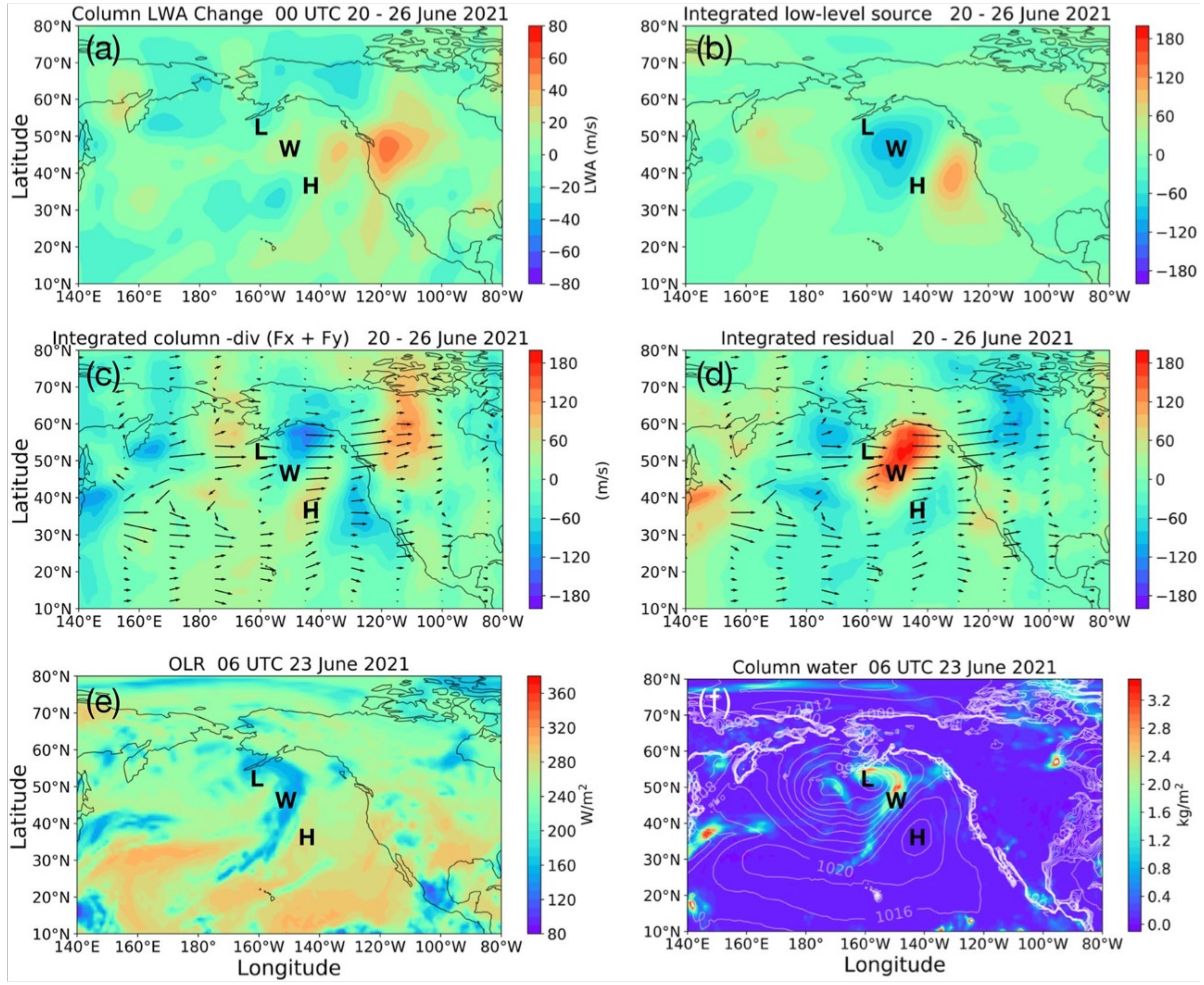
Emily Neal[1], Clare S. Y. Huang[1], and Noboru Nakamura[1]

[1]Department of the Geophysical Sciences, University of Chicago, Chicago, IL, USA

Abstract We investigate the meteorological and dynamical conditions that led to the extreme heat in the Pacific Northwest from late June to early July 2021. The extreme heat was preceded by an upper-level atmospheric blocking that snatched a warm pool of air from lower latitudes. A heat-trapping stable stratification ensued within the blocking anticyclone, raising the surface temperatures significantly. An upper-tropospheric wave breaking and the concomitant surface cyclogenesis off the coast of Alaska initiated the block formation. The regional local wave activity budget reveals that a localized diabatic source associated with this storm critically contributed to an enhanced zonal wave activity flux downstream, whose convergence over Canada drove the blocking. A simple reconstruction based on the observed wave activity budget predicts a 41 percent reduction in strength and a 10-degree eastward displacement of the block when the upstream diabatic source is reduced by just 30 percent.







Conclusions

- Well over seven decades after the first documentation of the phenomenon, the theory of blocking is still under development
- The approach varies greatly depending on how one characterizes blocking (e.g. finite amplitude Rossby waves vs. deterministic chaos)
- The role of theory is to extract a canonical dynamics of blocking out of diverse manifestations, helping to form a testable hypothesis (e.g. sensitivity to climate change) and improve predictability (e.g. bifurcation between weather regimes)
- Local wave activity budget provides a framework to bridge observation and theory

Rossbypalooza 2024: Climate and Extreme Events July 22 - August 2, Chicago

Application is open through April 28: http://www.rossbypalooza.org