An Overview of Atmospheric Transport

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  - mixing dominated by stretching, folding
  - 3D turbulence (e.g. breaking gravity waves) contributes to "small-scale" diffusivity, mixing

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Characteristics of large-scale transport

- Quasi 2D nature of large-scale extratropical flow characterized by:

Characteristics of large-scale transport

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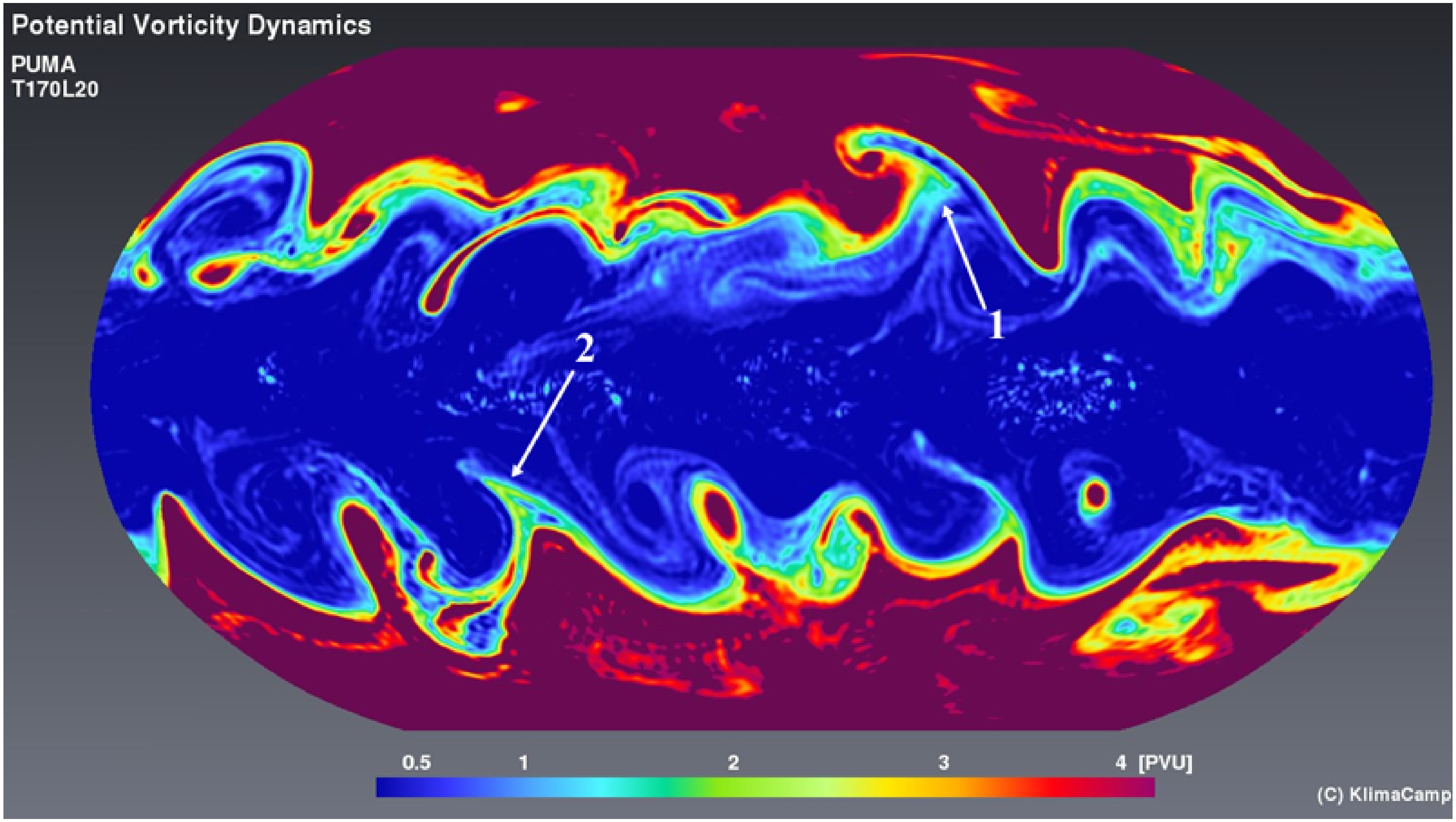
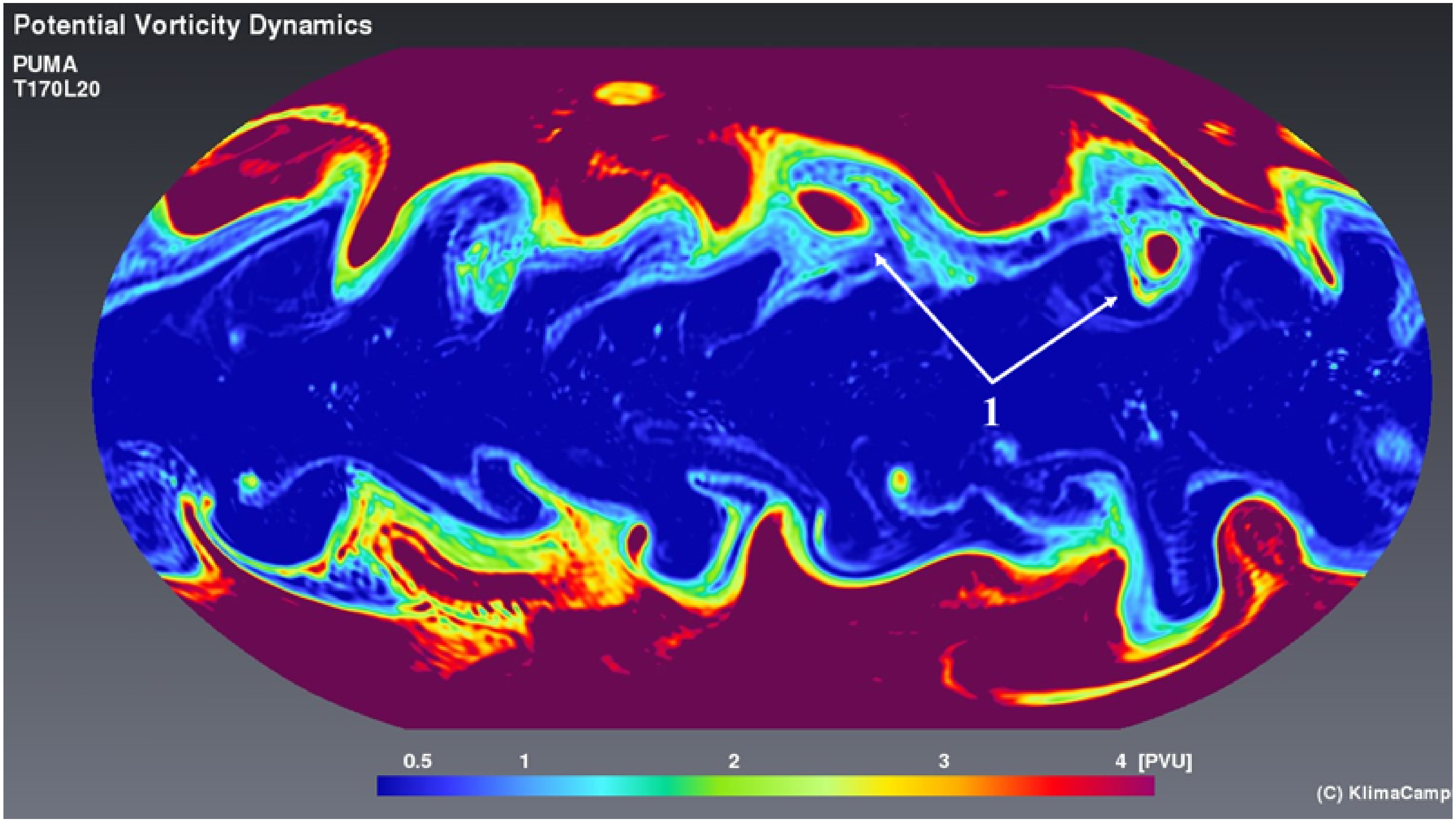


(www.clisap.de)

Characteristics of large-scale transport

- Quasi 2D nature of large-scale extratropical flow characterized by:

  closed eddies



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Characteristics of large-scale transport

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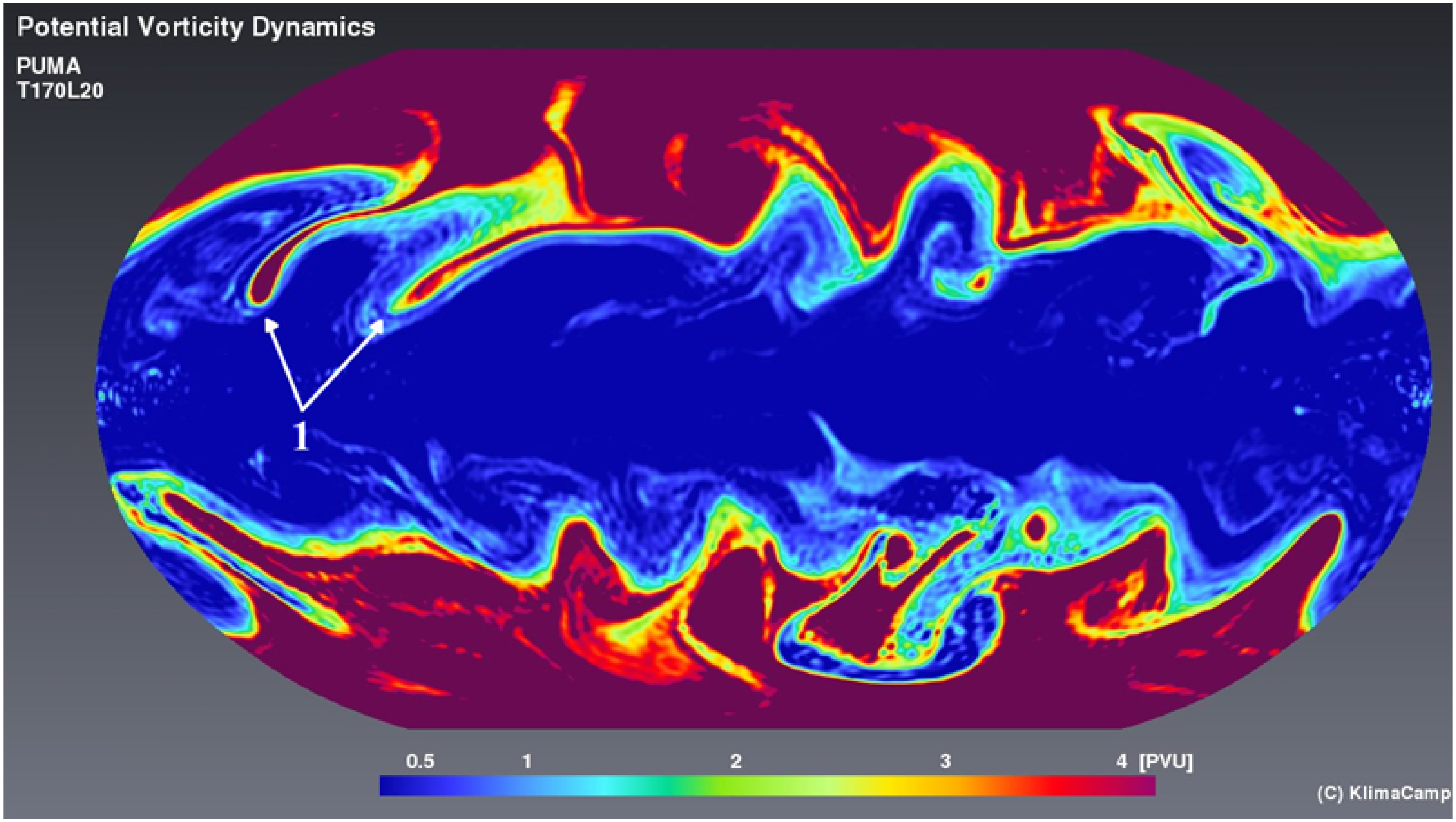

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Fundamental conservation laws

- For adiabatic, rotating flow, two fundamental conserved quantities:

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$$\theta = T\left(\frac{p_s}{p}\right)^{R/mc_p} \simeq T\left(\frac{p_s}{p}\right)^{2/7}$$

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  Potential vorticity (PV)

$$\Pi = \frac{(\nabla \times \mathbf{u} + 2\boldsymbol{\Omega}) \cdot \nabla\theta}{\rho}$$

  where

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- Large-scale balance allows *inversion* of Π for velocity, temperature, mass
- Spatial gradients of PV on θ-surface inhibit horizontal motion of air parcels, result in *Rossby waves*

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PV gradients, transport, mixing

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e.g. stratospheric polar vortex surrounded by Rossby wave surf zone

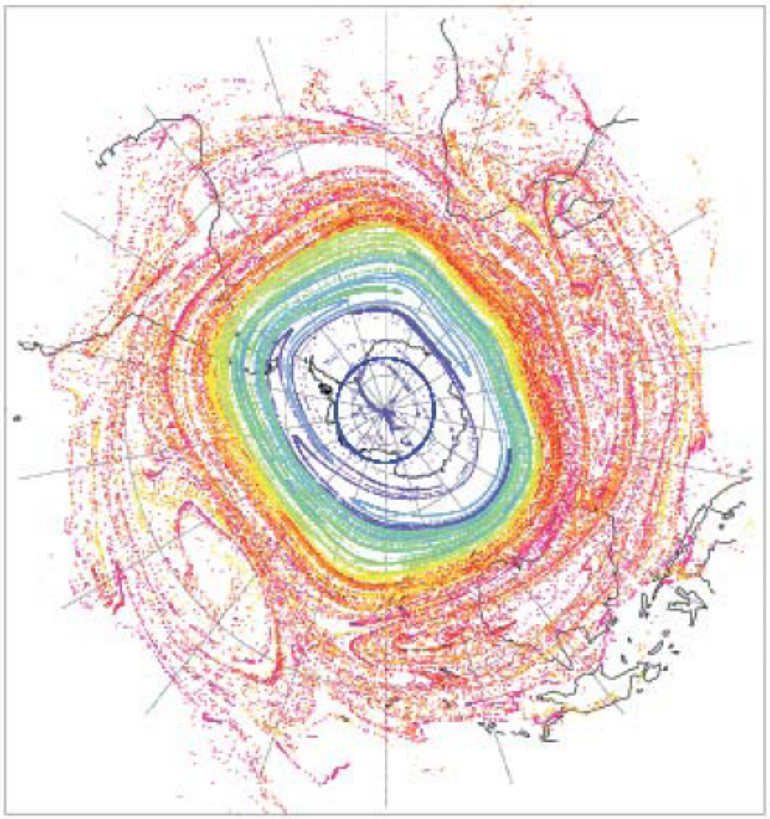


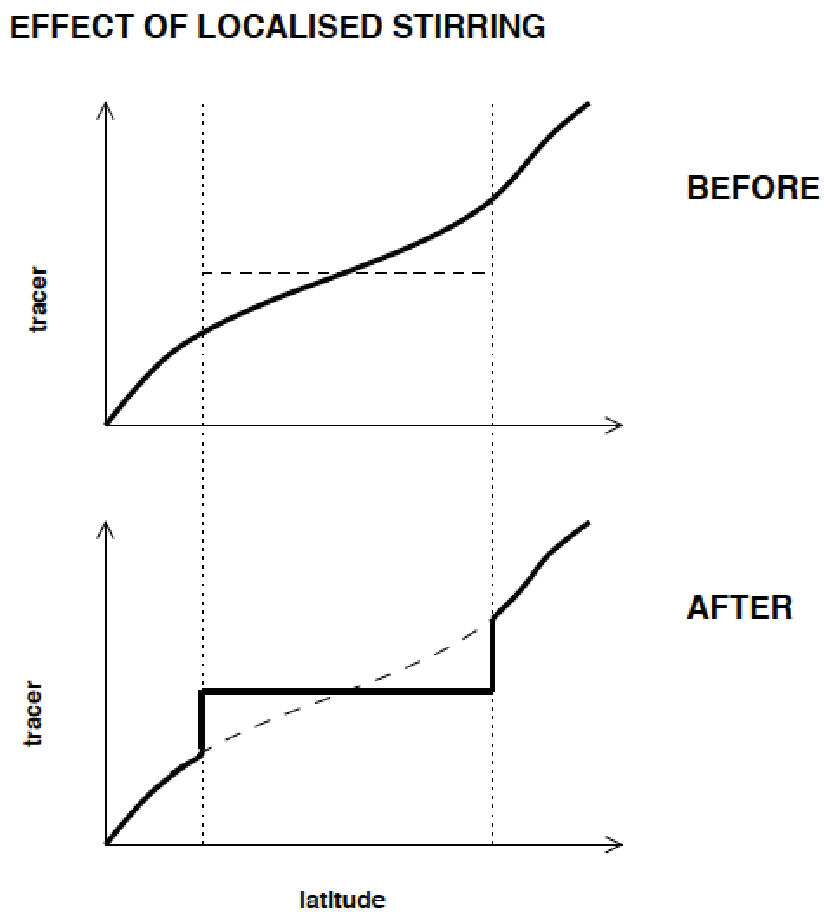
Fig. 10. Results of a 30-day particle advection calculation using isentropic winds at 450 K (approximately 17 km altitude), in the heart of the wintertime polar ozone layer, from the Canadian Middle Atmosphere Model for a model July. The particles were initially located along rings of constant latitude, with each ring indicated with a different color. Note the strong isolation of the polar vortex, compared to the mixing in the surf zone outside. Figure courtesy of Keith Ngan, University of Toronto. Reprinted with permission from Shepherd (2000), copyright Elsevier Science.

(Shepherd, 2007)

PV gradients, transport, mixing

- PV gradients result from planetary geometry (β-effect), flow, stratification
- Strong PV gradients (e.g. jets) barriers to transport

  but can themselves be produced by mixing

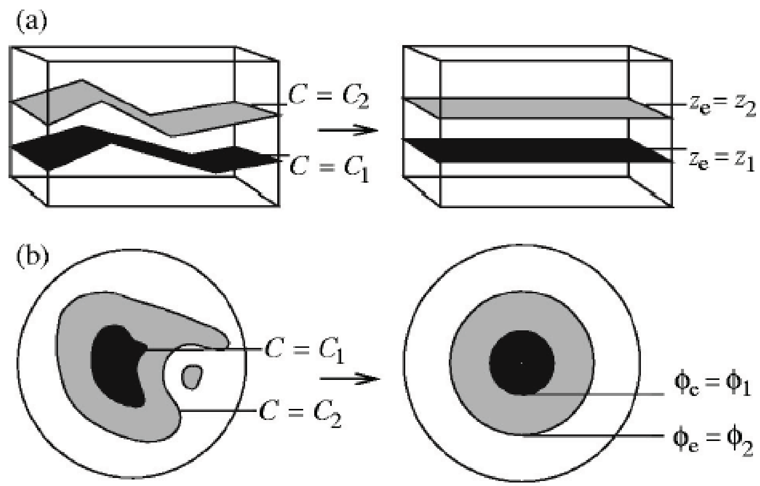


(Haynes, 1995)

Effective diffusivity

- Tracer conservation:

$$\partial_t c + \mathbf{u} \cdot \nabla c = \nabla \cdot (\kappa \nabla c)$$



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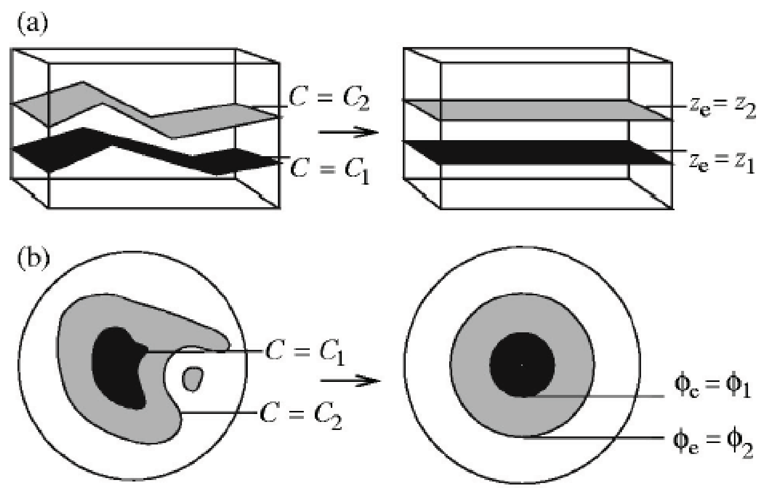
$$\frac{\partial C(A,t)}{\partial t} = \frac{\partial}{\partial A}\left(K_{eff}(A,t)\frac{\partial C(A,t)}{\partial A}\right)$$



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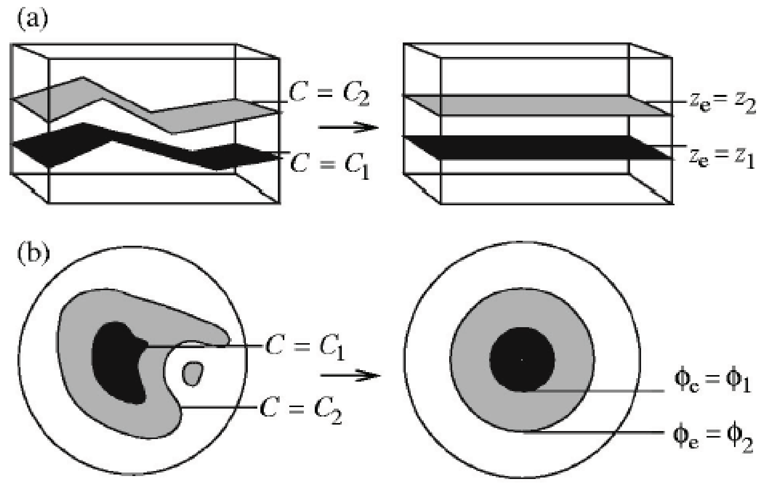

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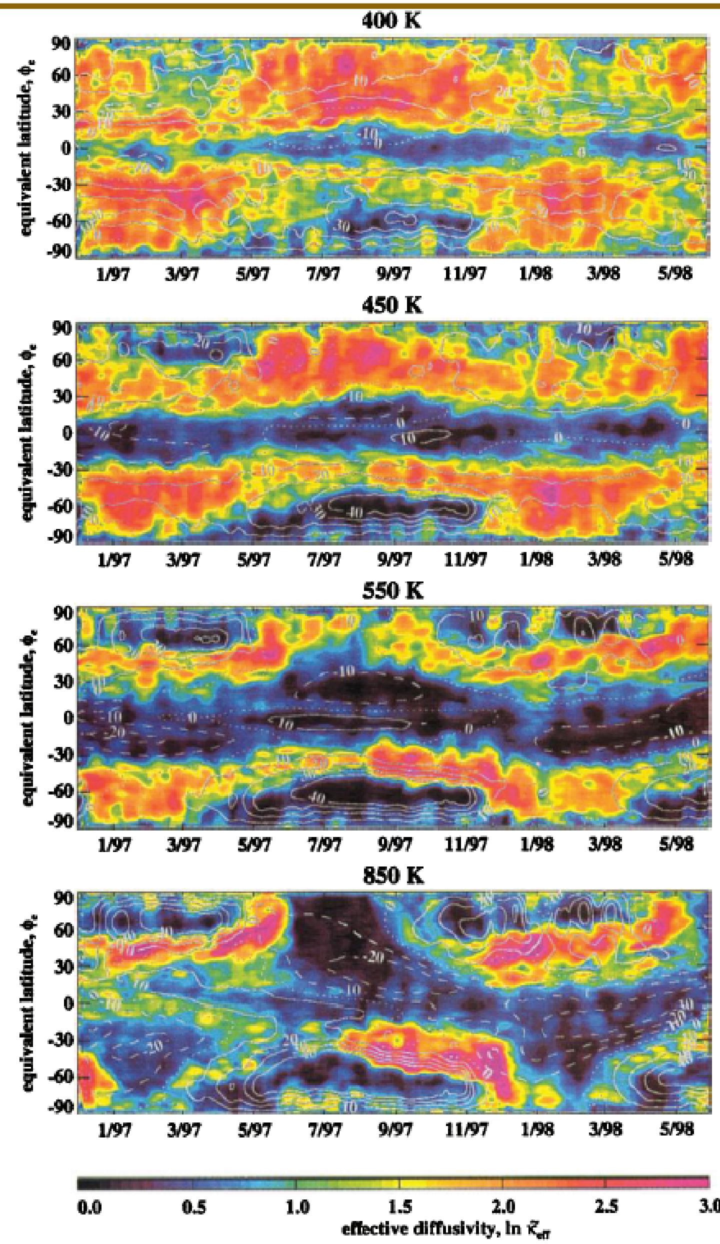

(Haynes and Shuckburgh, 2000)

Effective diffusivity vs. FTLE

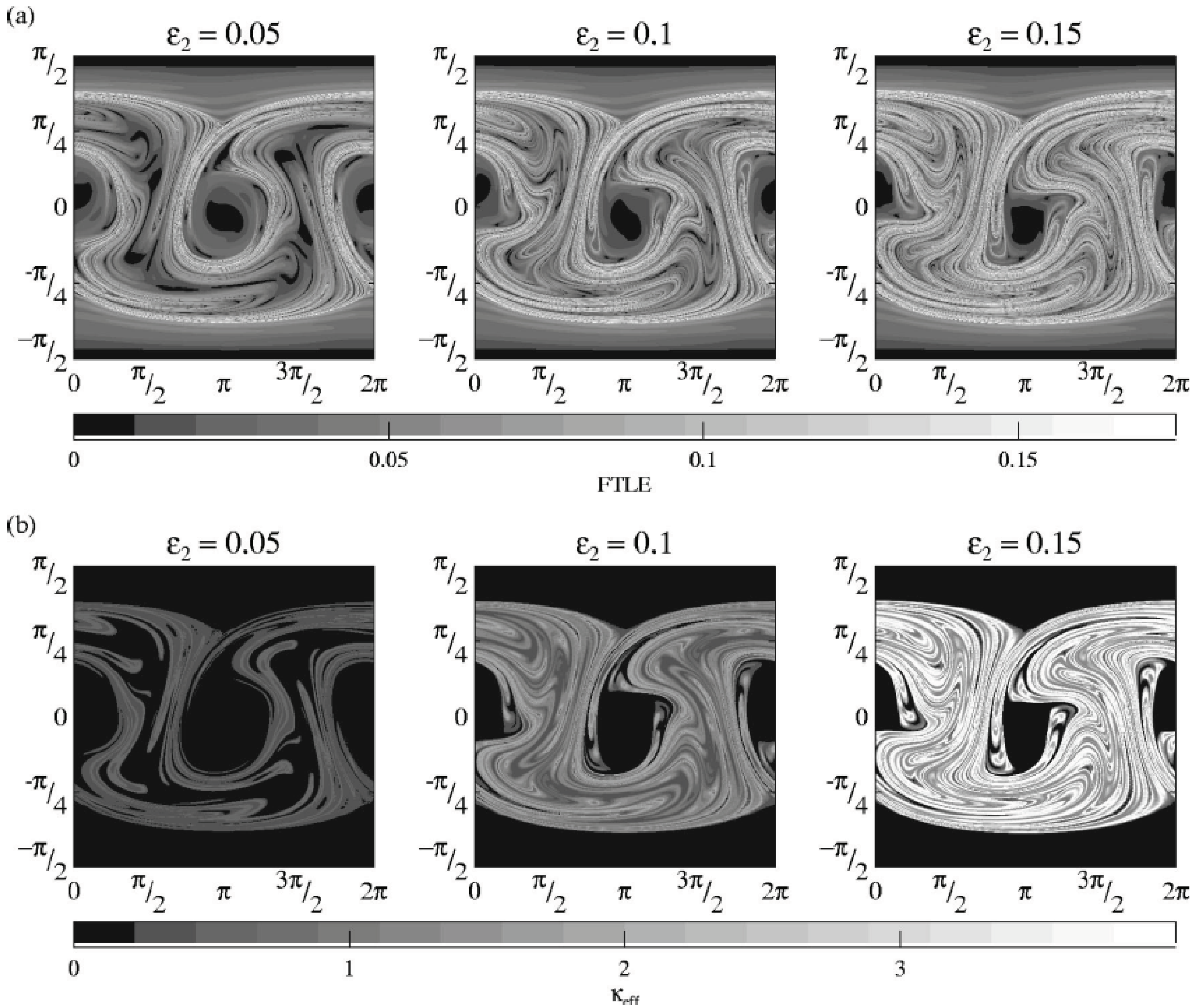

FIG. 14. (a) Finite-time Lyapunov exponents at $T = 10\tau$ and (b) effective diffusivity (lower panel) for various ϵ_2, scale is $\times 10^{-3}$ for κ_{eff}.

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Time-periodic flow; metrics show similarities and differences (Shuckburgh and Haynes, 2003)

Greens function methods

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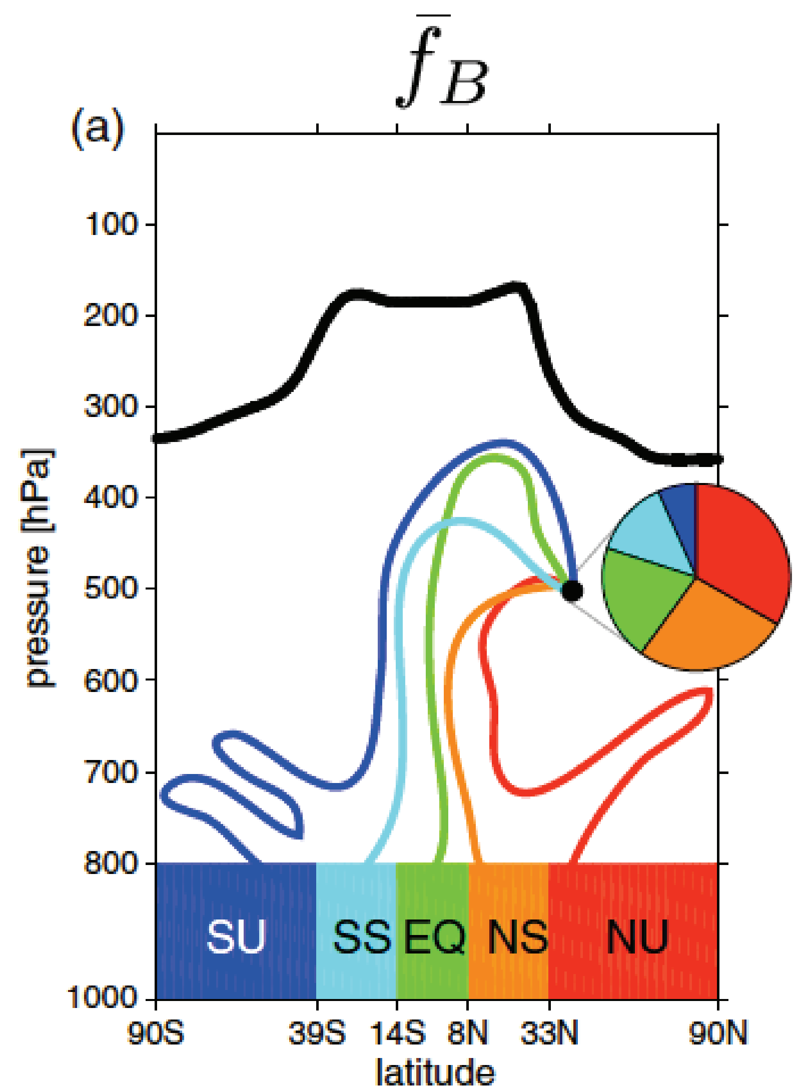

Zonal- and time-mean (Orbe et al., 2013)

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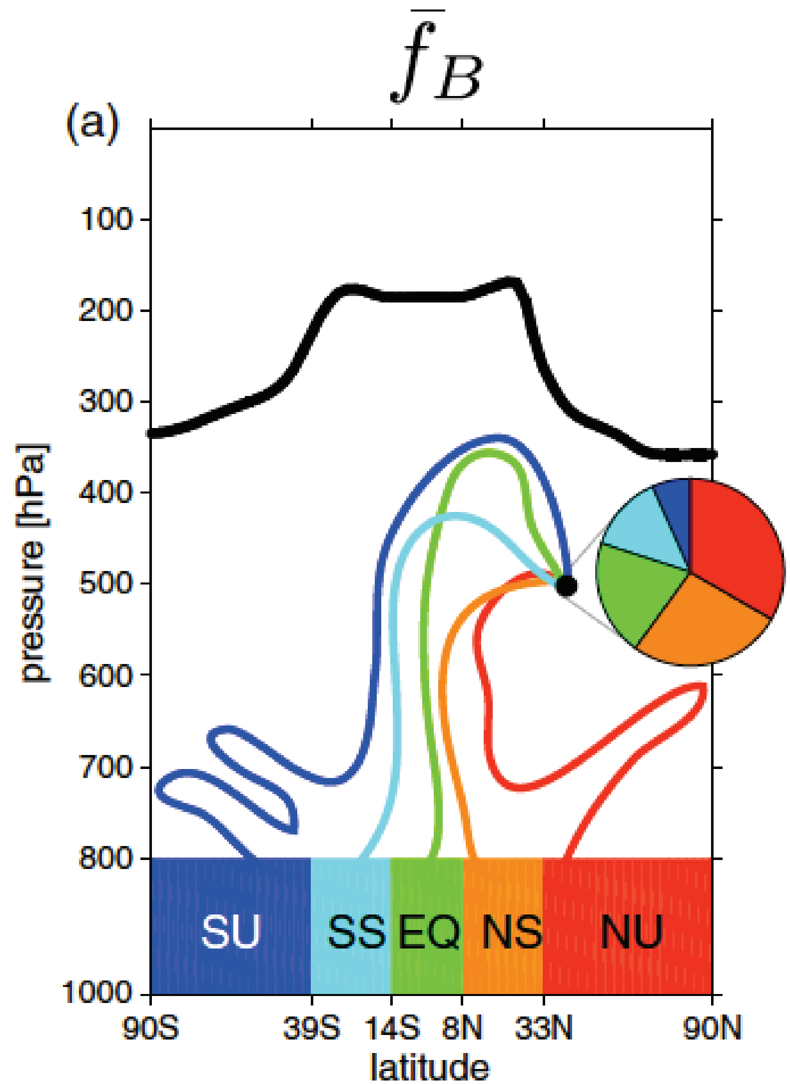

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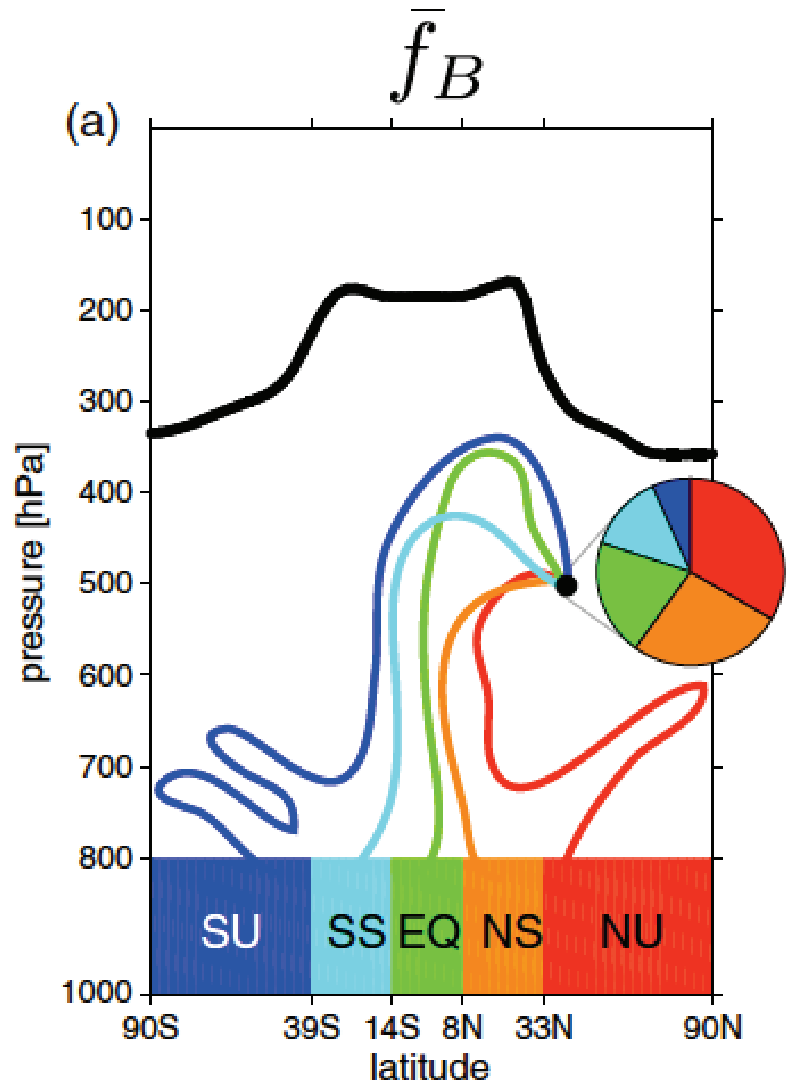

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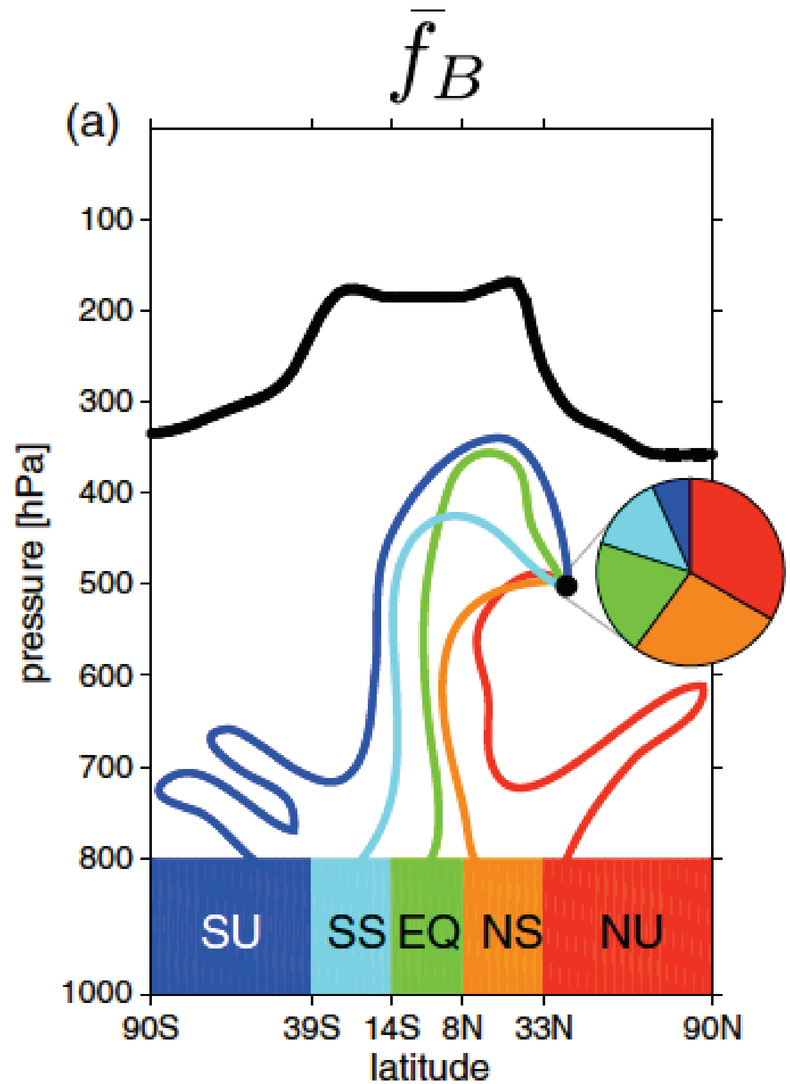

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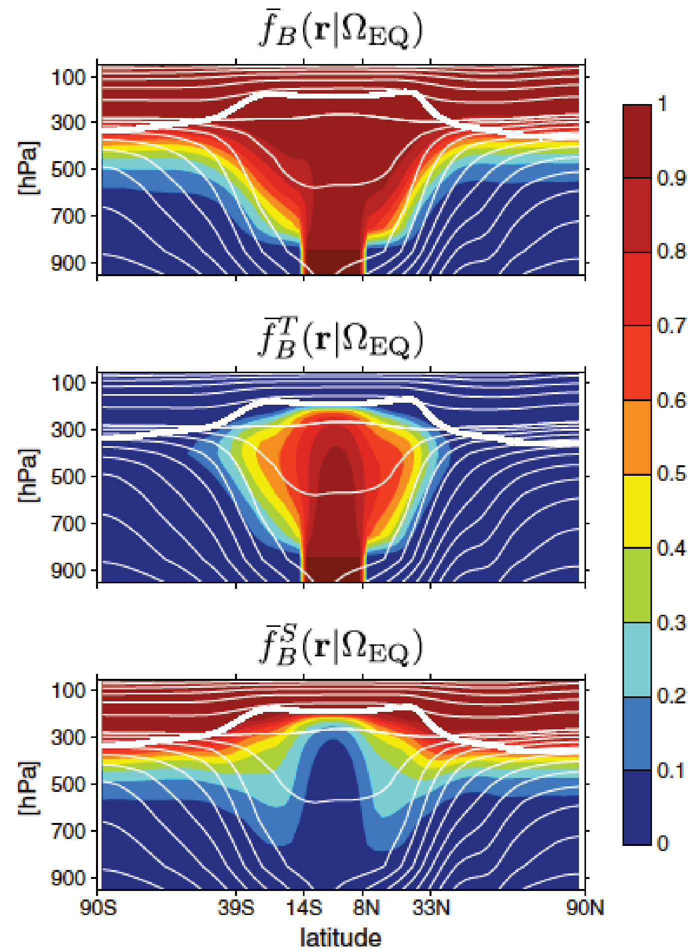

Figure 5. The REF climatology of the partitioning of the Ω_{EQ} PBL air-mass fraction $\bar{f}_B$ (top) into its troposphere-only component $\bar{f}_B^T$ (center) and the component that does visit the stratosphere $\bar{f}_B^S = \bar{f}_B - \bar{f}_B^T$ (bottom). The thick white line indicates the tropopause, and the thin white lines indicate the isentropes (contours every 30 K).

Zonal- and time-mean (Orbe et al., 2013)

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Transfer operator methods

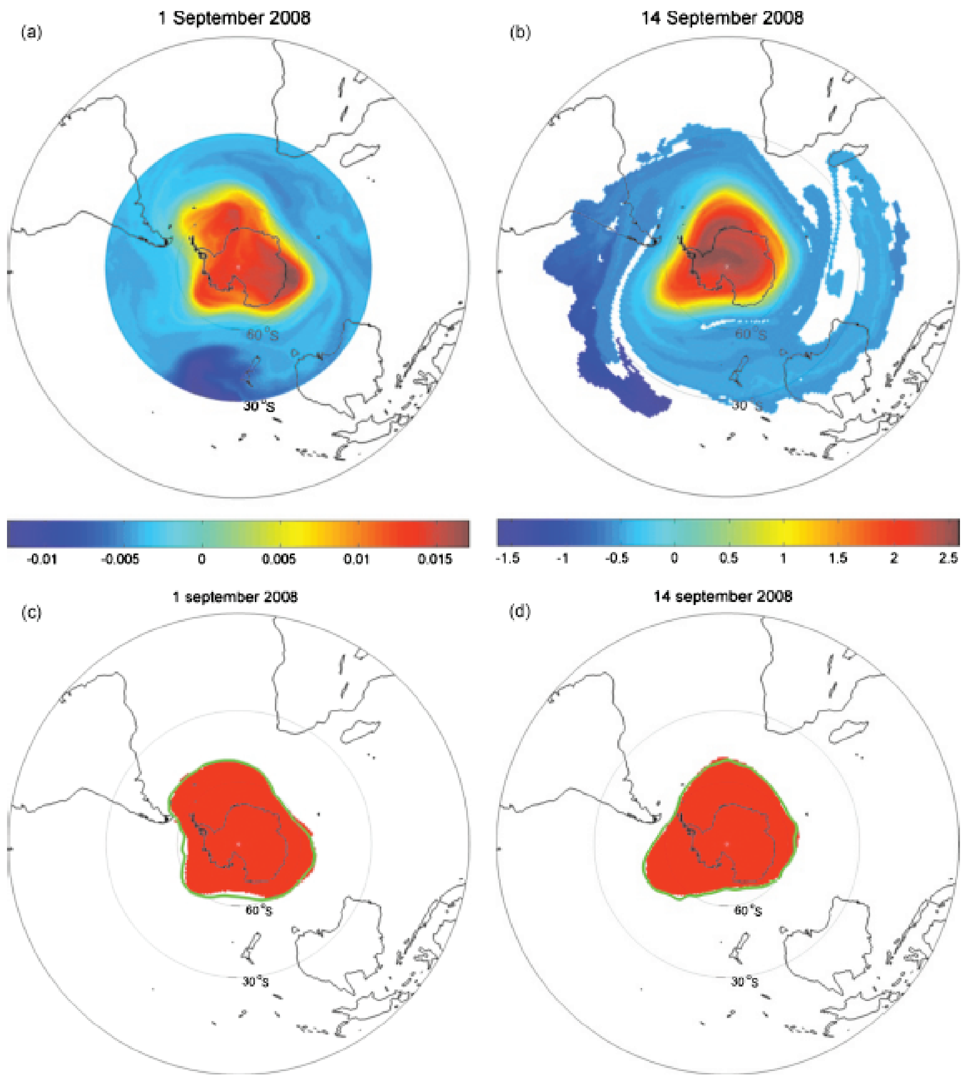
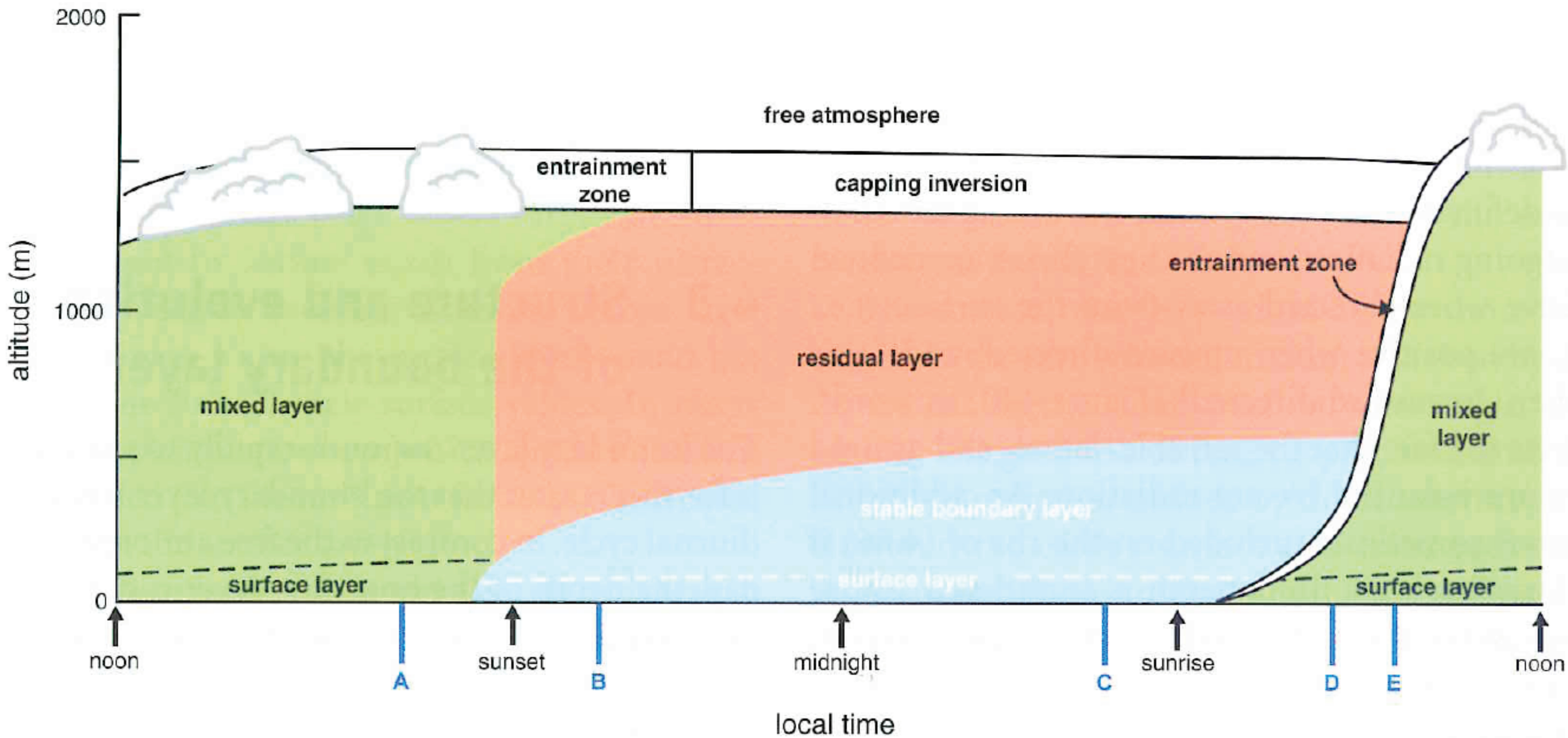


FIG. 3. (Color online) (a) Graph of x (1 September 2008). (b) Graph of y (14 September 2008). (c) The solid (red) set represents the coherent set A_t (1 September 2008) obtained from Algorithm 1. The solid (green) curve illustrates the vortex edge as estimated using PV. (d) As for (lower left) at 14 September 2008.

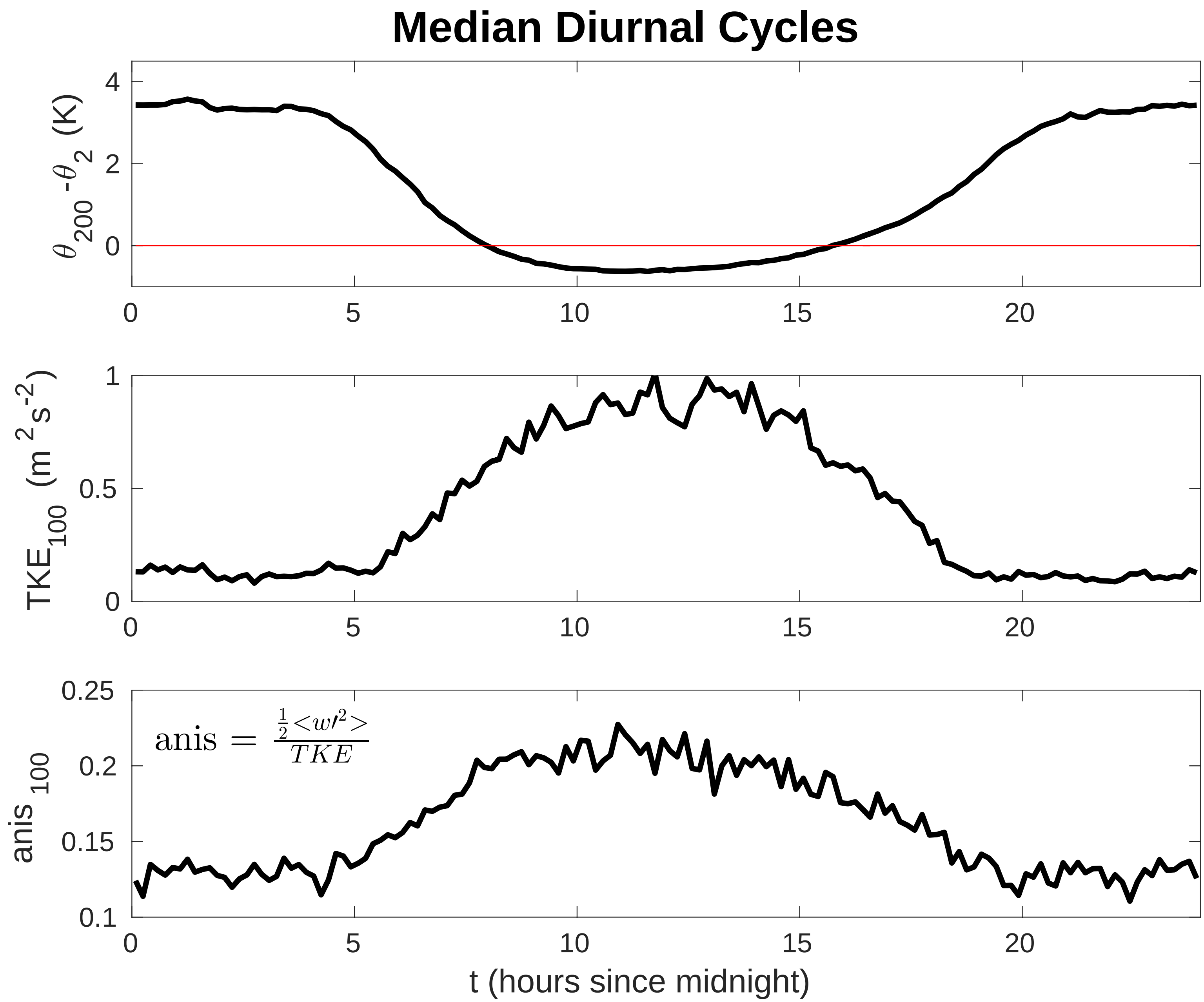
475 K, $1.5° \times 1.5°$, ECMWF (Froyland et al., 2010)

Typical evolution of fair-weather boundary layer



(Markowski and Richardson, 2010)

Diurnal cycle of stratification, turbulence at Cabauw



Coherent structures in the SBL

		Periodicity	
	Single event	Few cycles	Cyclic
Sine	Solitary modes	Dirty waves $1 < \text{cycles} < n$ $\delta A > A_t,\ \delta P > P_t$	Monochromatic waves $\text{Cycles} > n$ $\delta A < A_t,\ \delta P > P_t$
Ramp	Isolated ramps	Instabilities	
Step	Microfronts	Instabilities	
Top hat	Wind pulses		
Less defined	Two-dimensional modes		

Approximate shape in time domain

Figure 4

A schematic of different idealized shapes of structures found in time series. Unspecified n defines the minimum number of cycles required in order to be cyclic. A_t is the maximum allowed change of amplitude between subsequent cycles for potential inclusion into the cyclic category. P_t is the maximum change in period between subsequent cycles for potential inclusion into the cyclic category. The phase between variables is additional information not included here.

Mahrt, *Ann. Rev. Fluid Mech.*, 2014

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Transport by intermittent turbulence in the VSBL

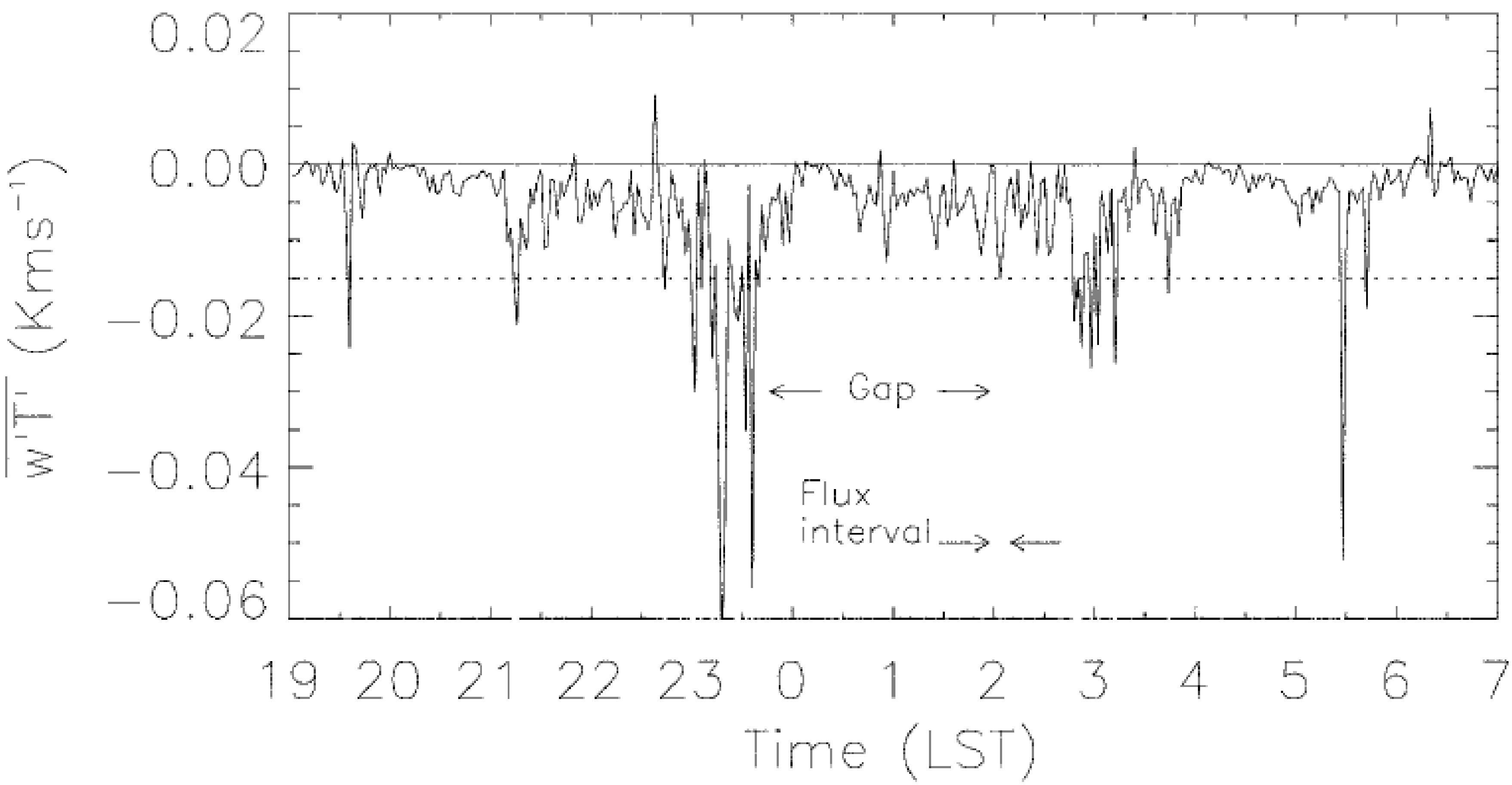

Figure 1. Time series of temperature fluxes from the CASES99 experiment calculated with 120-s flux intervals. The flux threshold value of –0.015 K m s^{-1} chosen for this example is indicated by the dotted line and the grey areas indicate turbulent events.

(Doran, 2004)

Intermittent turbulence in the VSBL

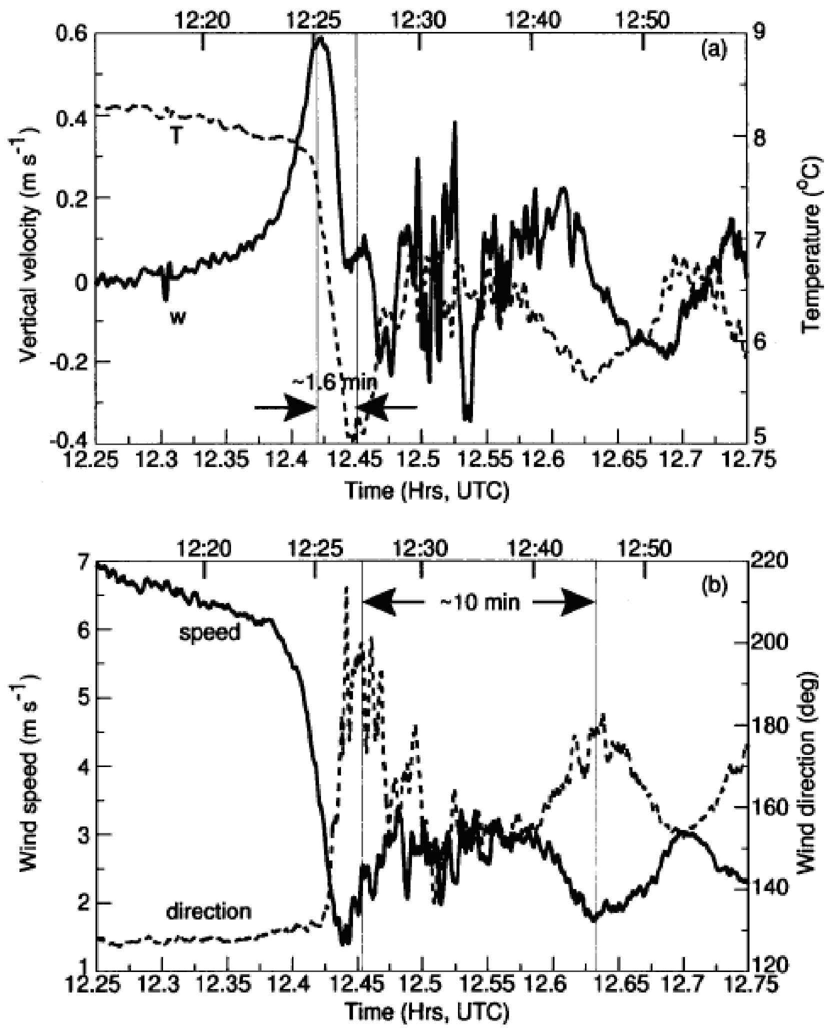

Figure 10. Time series of (a) vertical velocity and air temperature at 55 m and (b) wind speed and direction at 25 m during the passage of the internal gravity wave. Note that the large temperature fall lagged about 1.6 min behind the large vertical velocity increase associated with the internal gravity wave and the period of the internal gravity wave is about 10 min.

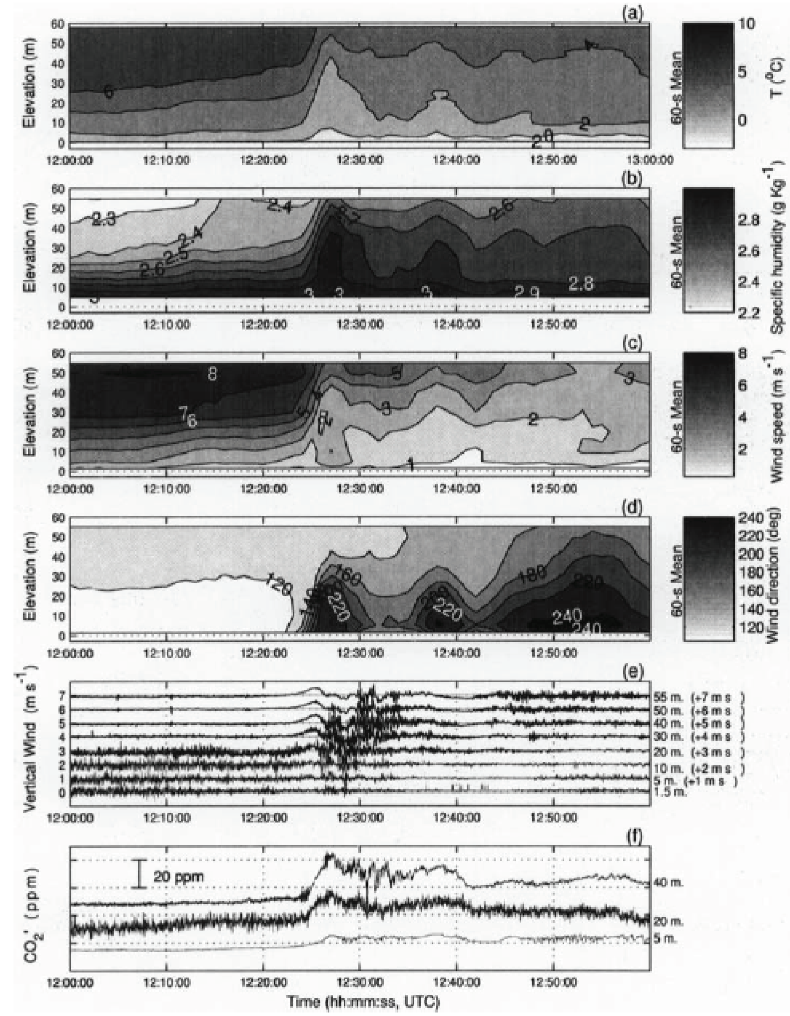

Figure 11. Time-height cross-section of (a) air temperature (thermocouple), (b) specific humidity (aspirated Vaisala), (c) wind speed, (d) wind direction, (e) vertical velocity at eight levels, and (f) carbon dioxide perturbation (CO_2') at 5 m, 20 m, and 40 m during the passage of the internal gravity wave. Wind speed and direction are from the prop-vanes. Vertical velocity is from the sonic anemometers with the zero value shifted by the value on the right side of each time series for better viewing of the turbulence as a function of time and height.

(Sun et al. 2003)

Coherent structures in the SBL

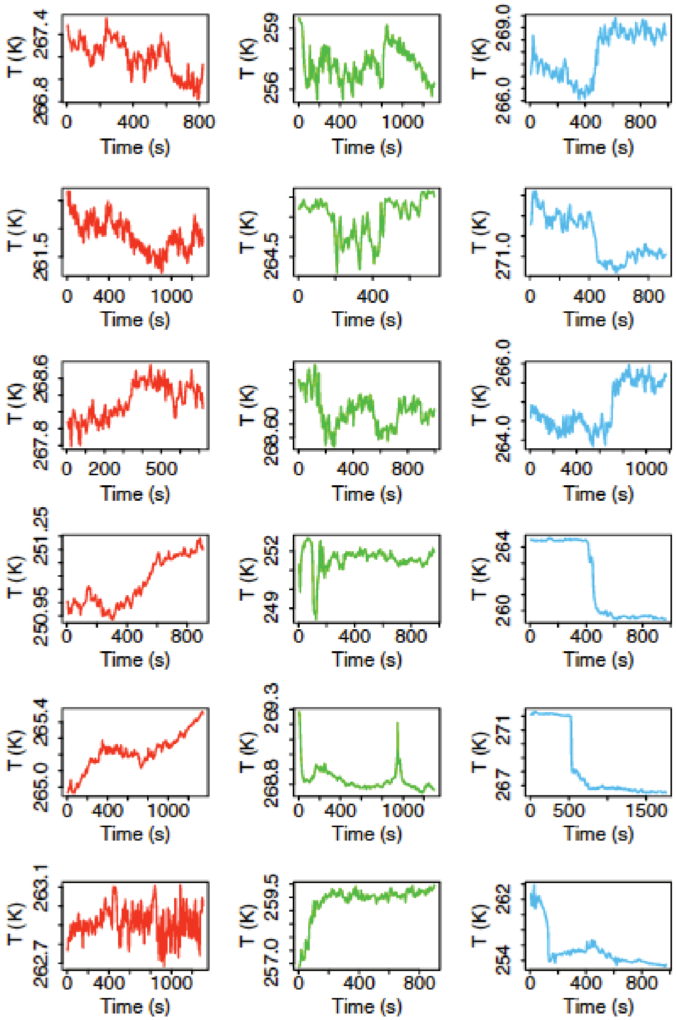

Figure 2. Examples of events in clusters 1 (left panels), 2 (middle panels) and 3 (right panels), showing the three events nearest to (top three panels), and the three furthest from (bottom three panels), the cluster centre.

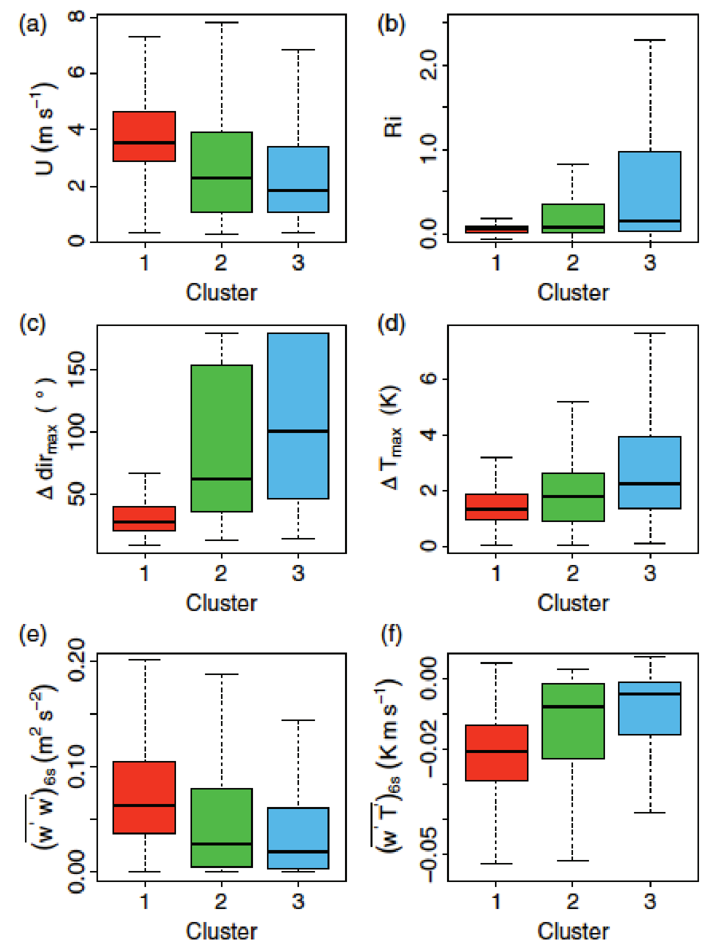

Figure 3. Boxplots of main physical characteristics for clusters 1, 2 and 3, at level 2 (2 m): (a) U, (b) Ri, (c) Δdir_{max}, (d) ΔT_{max}, (e) $\overline{w'w'}_{6s}$ and (f) $\overline{w'T'}_{6s}$. The line in each box represents the median of that cluster, while the bottom and top of the box are the 25th and 75th percentiles. The whiskers extend to the minimum or maximum values within 1.5 times the box height from each side of the box. The subscript '6s' denotes the 6 s averaging interval for the fluxes.

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(Kang et al. 2015)

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  - What tools are available to help develop stochastic parameterizations of intermittent turbulence associated with coherent structures in the SBL?

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- Flow along constant θ surfaces quasi-2D with streamfunction ψ

Quasigeostrophic dynamics

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- Dynamics due to (relatively) small perturbations from *geostrophic balance*
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with dynamics

$$\partial_t q + \partial_x \psi \partial_y q - \partial_y \psi \partial_x q = S$$

where z is a "vertical" coordinate (relative to the isentropes)

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- Poisson equation for q (+ BCs) can be inverted to obtain all dynamically relevant quantities

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Global transport structure

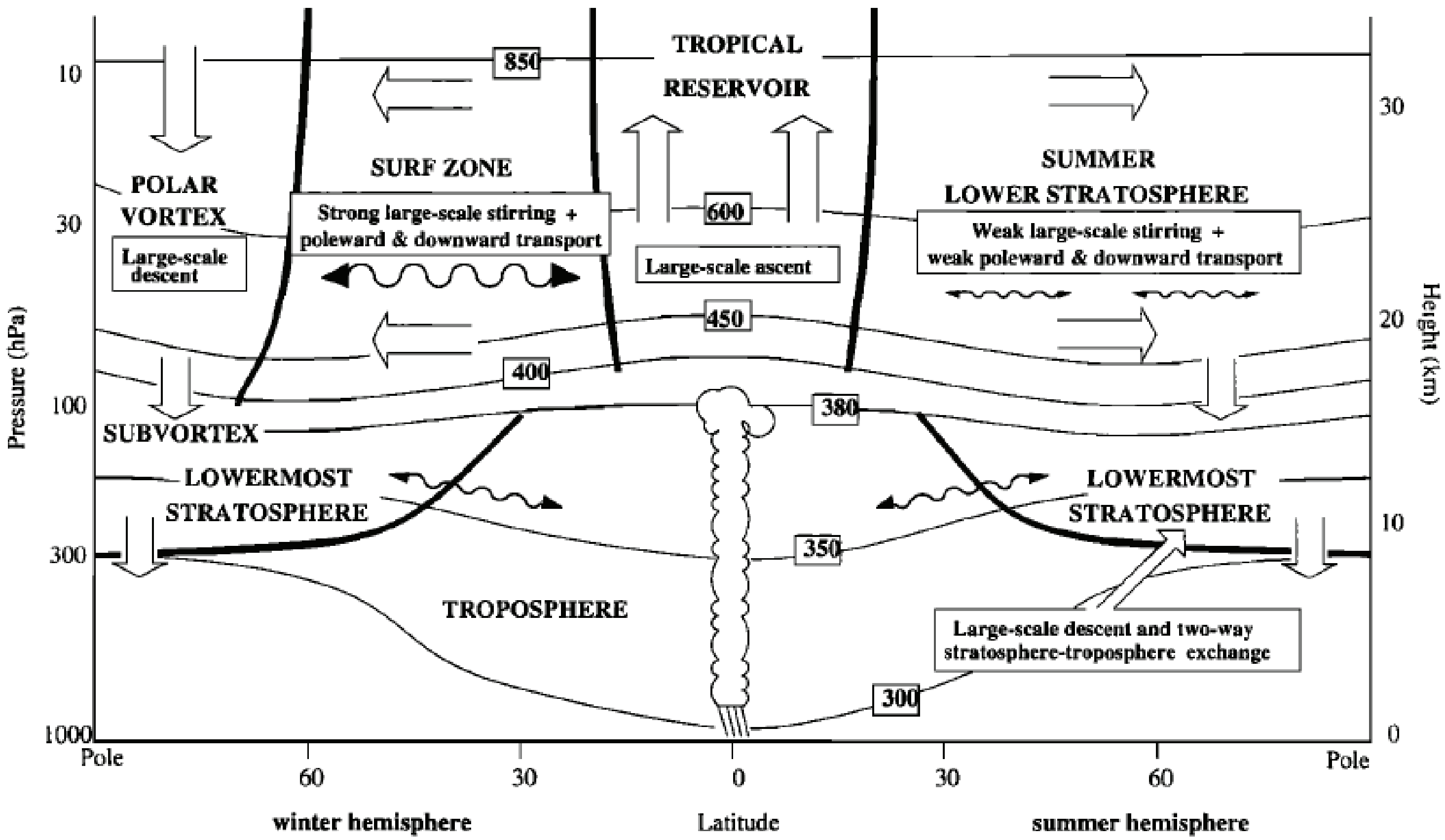

Figure 1. Schematic diagram showing pattern of transport and mixing in the troposphere and stratosphere: thin curves show selected isentropic surfaces, labeled by potential temperature; large arrows show transport due to the zonally averaged diabatic circulation, the vertical component of which is across isentropic surfaces; wavy arrows show eddy transport along isentropic surfaces; the stratosphere above 400 K is divided into different regions (vortex, surf zone, tropical reservoir, and summer extratropics) by eddy-transport barriers, indicated by thick curves; the atmosphere below 400 K is divided into different regions (troposphere and lowermost stratosphere) by eddy-transport barriers coincident with the extratropical tropopause, with the lowermost stratosphere being distinguished from the rest of the stratosphere by the fact that it is accessible from the troposphere along isentropic surfaces; the part of the stratosphere below the polar vortex is the "sub-vortex."

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