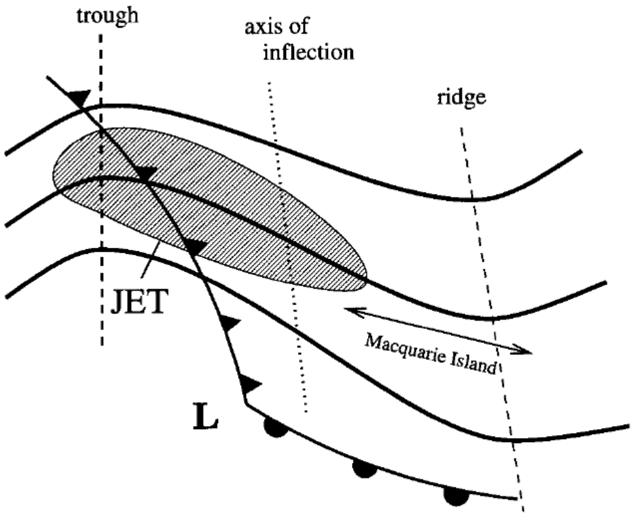
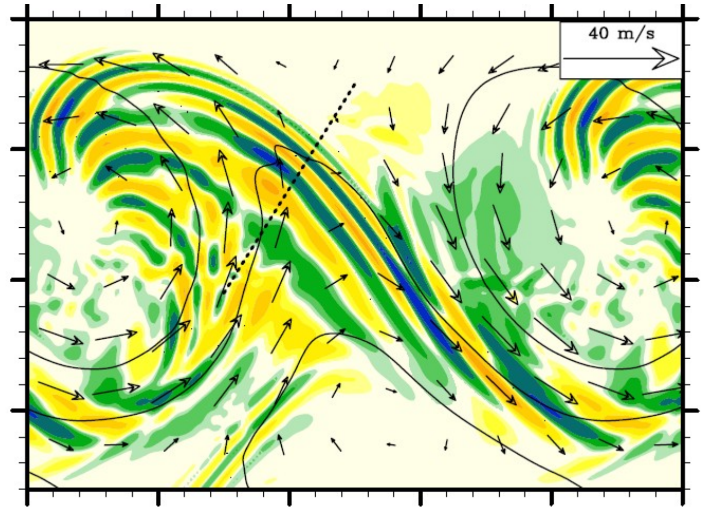
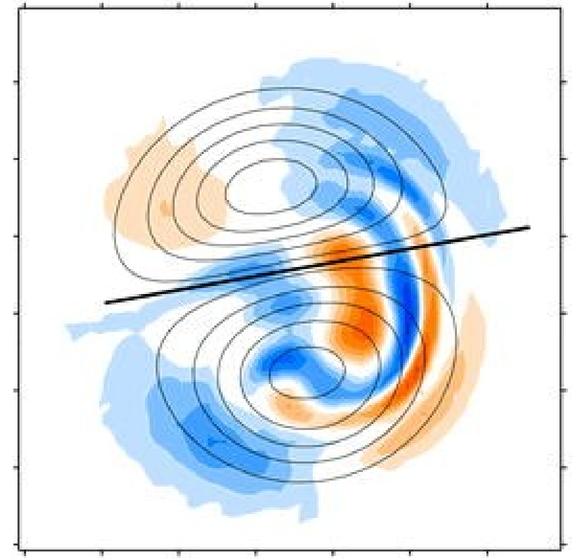
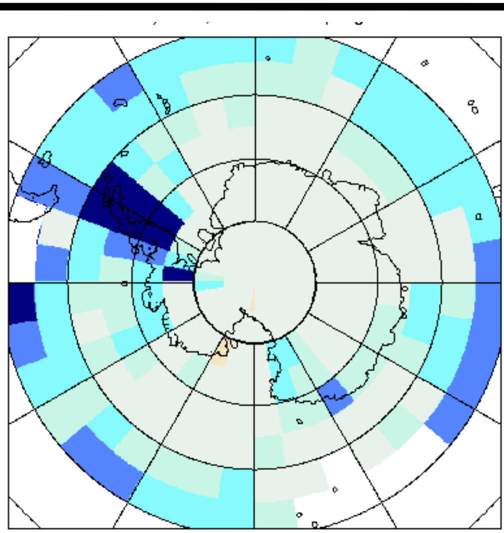


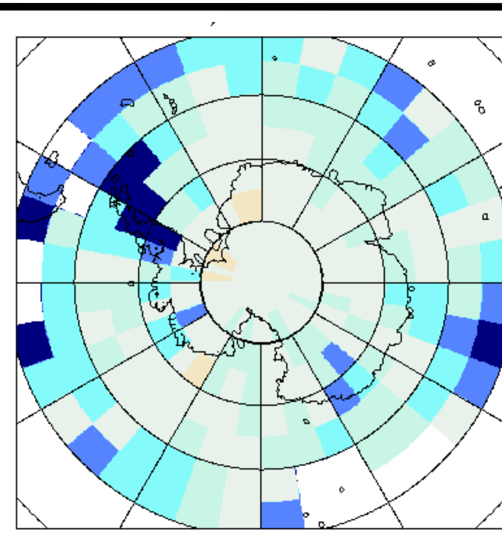


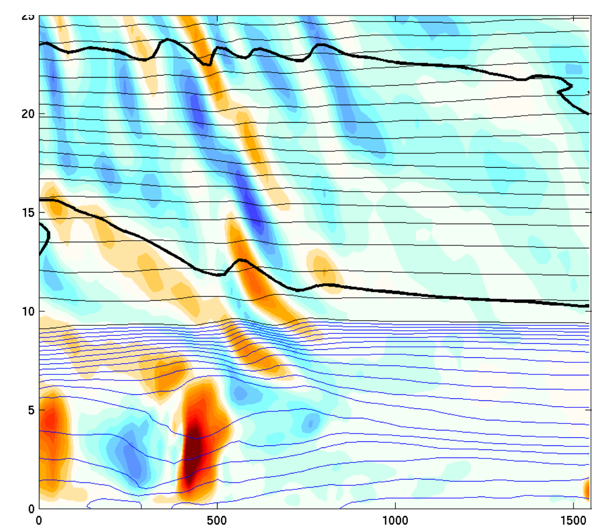


Gravity waves generated from jets and fronts

Riwal Plougonven,
Laboratoire de Météorologie Dynamique,
Ecole Polytechnique, Palaiseau, France







Outline

Early observations

Theoretical understanding of jet exit region waves

Numerical simulations // balloon observations

Case study

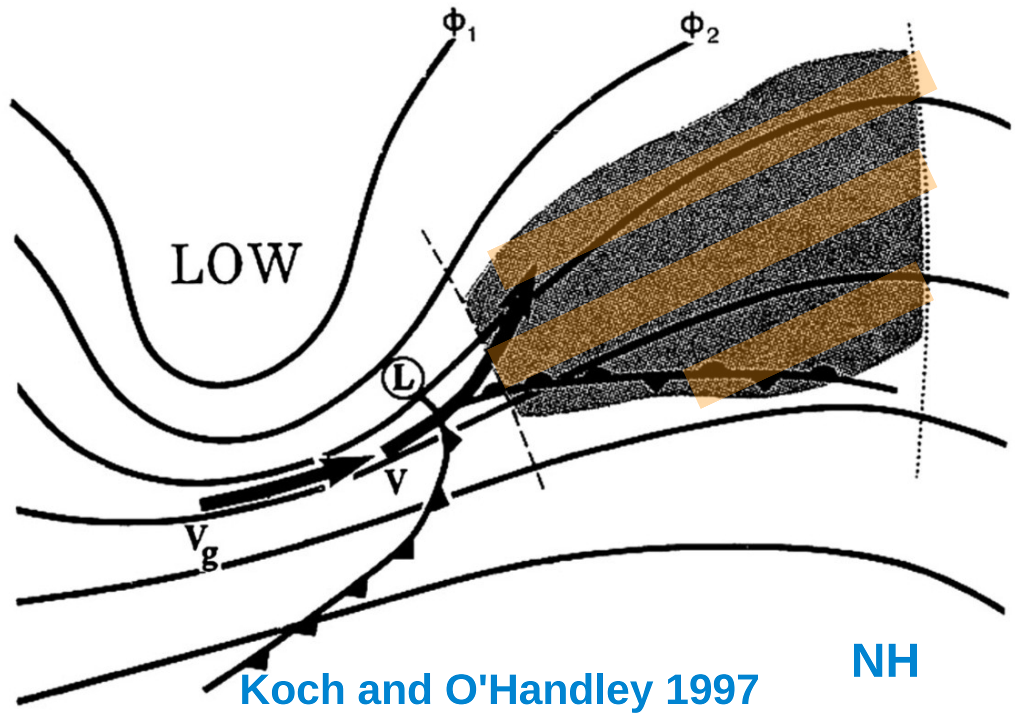
Conclusion and discussion

(Questions, issues in green)

Favorable configuration for IGW near jets and fronts

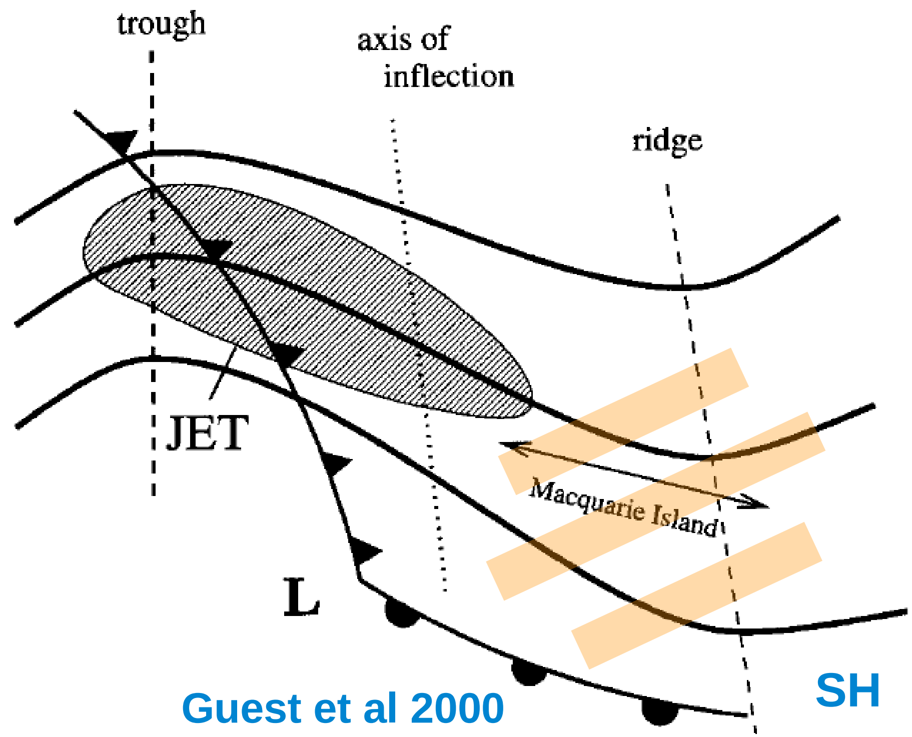
Identified from observational case studies (*Uccelini & Koch 87...)*

Region with IGW



Koch and O'Handley 1997

NH



Guest et al 2000

SH

Questions, issues :

1- generation / propagation ?

2- only configuration ?

3- how important relative to other sources ?

4- quantities to describe ?

3- Importance of jet/front generated waves relative to other sources ?

Analysis of small-scale motions measured by aircraft

Variances are **related to features of the flow**

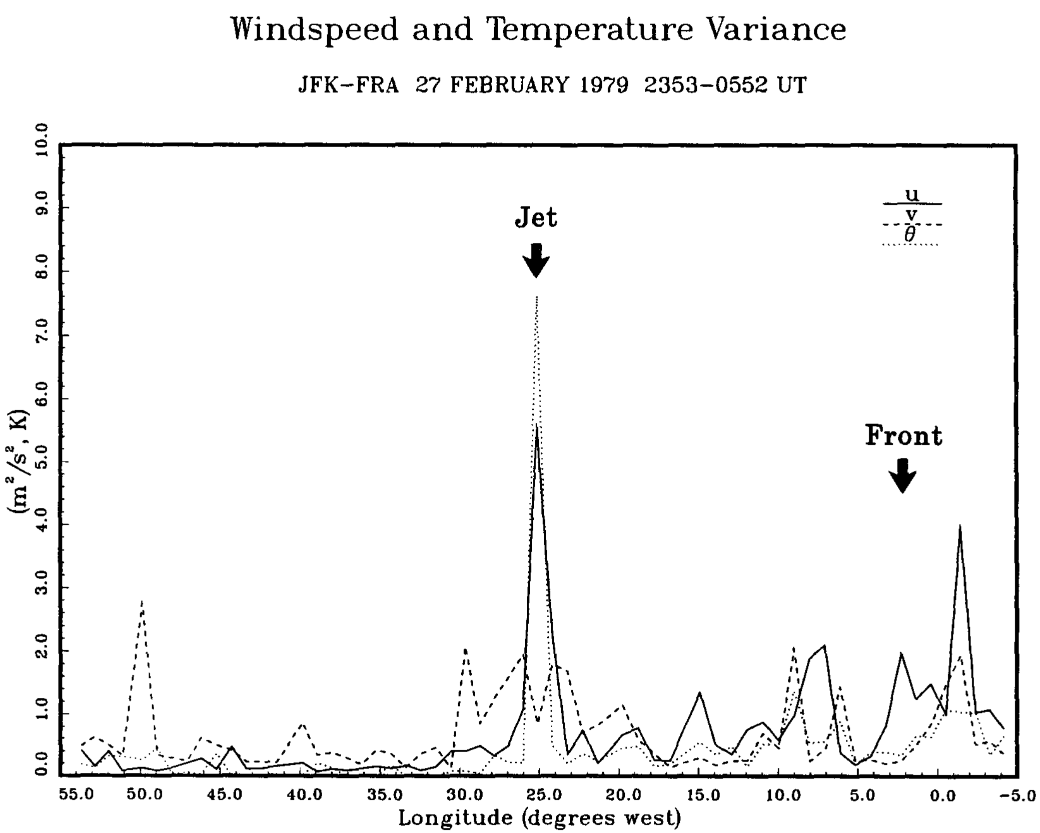
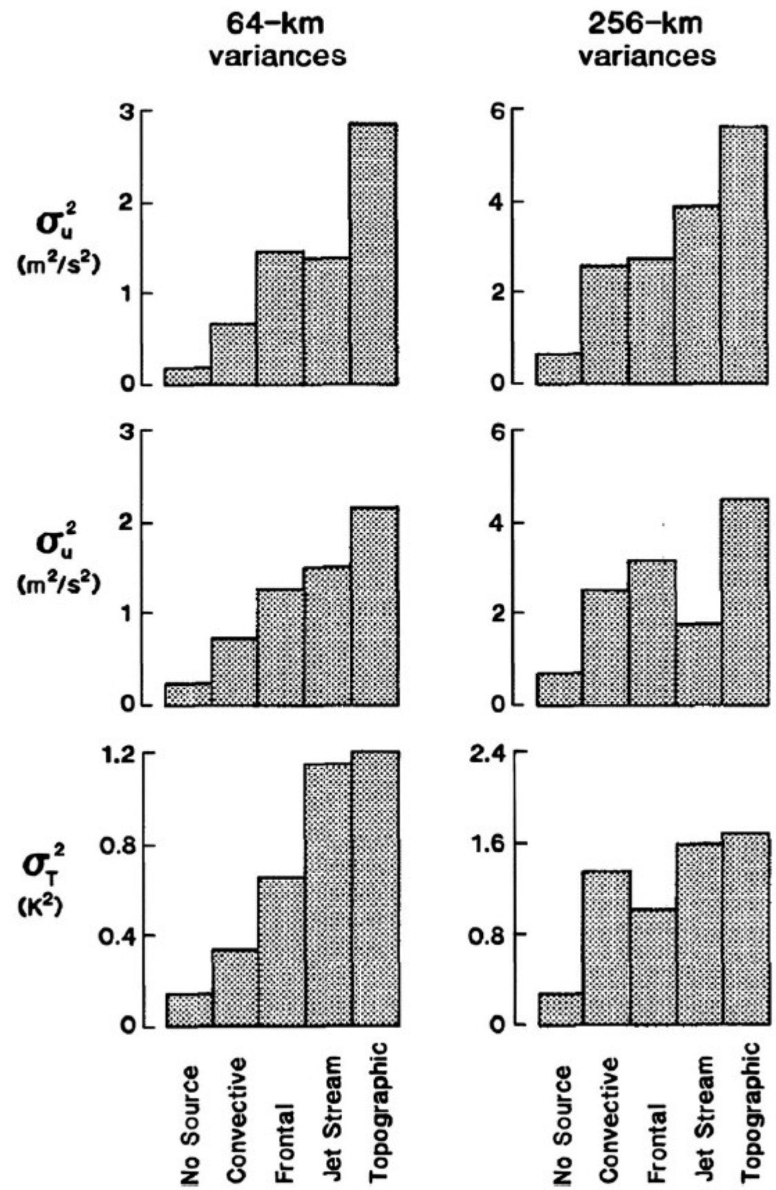


FIG. 12. As in Fig. 11, but for the 64-km variances of u, v, and T from ~54°W to 5°E.



Jet/front waves of comparable importance to topography

Fritts and Nastrom 92

Baroclinic instability

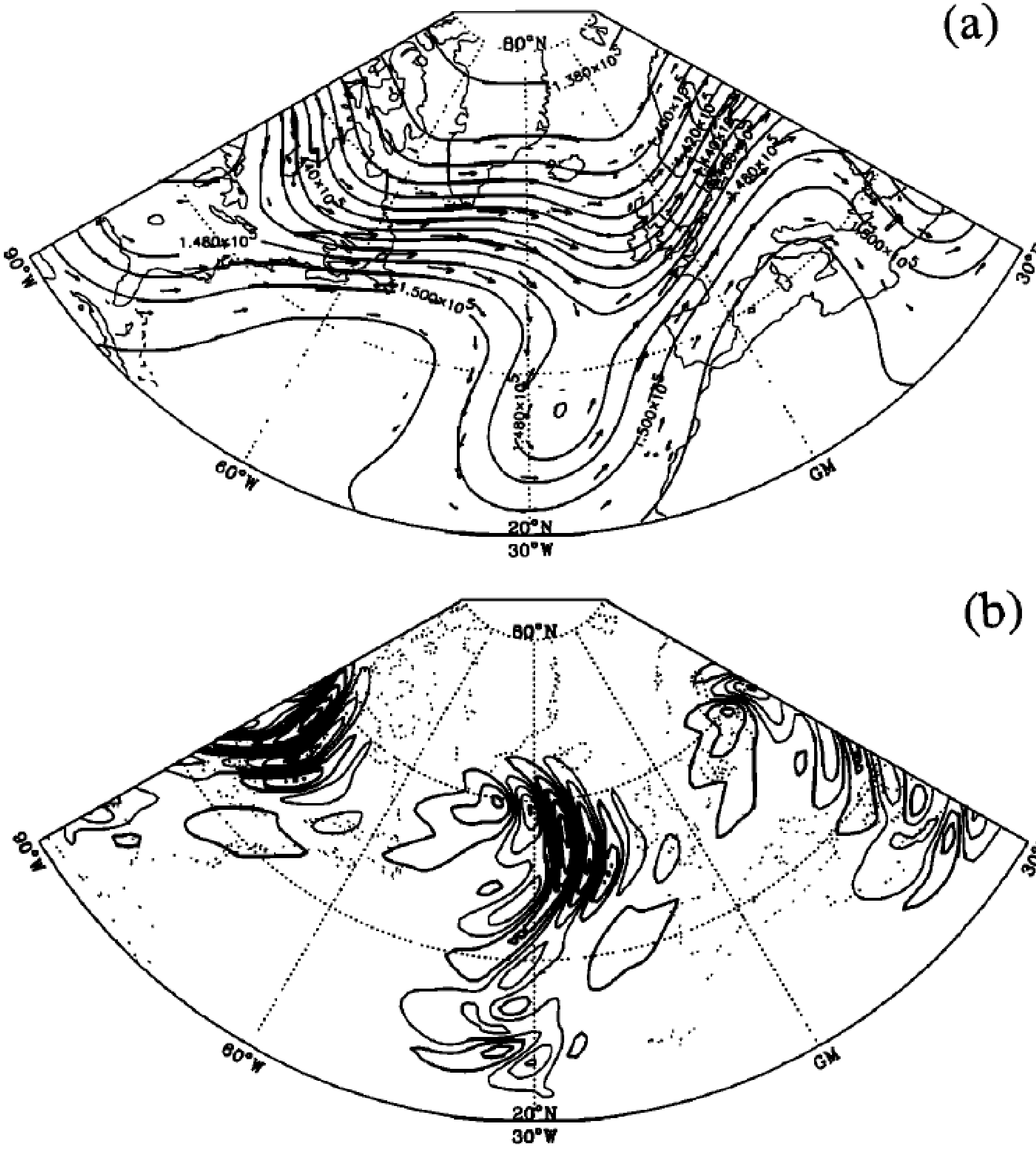
Numerical simulations of an idealized baroclinic instability

GCM with no bottom topography

IGW generated by upper-level jet, **downstream of a jet streak**

Advection of the waves into the rest of the jet (IGW...)

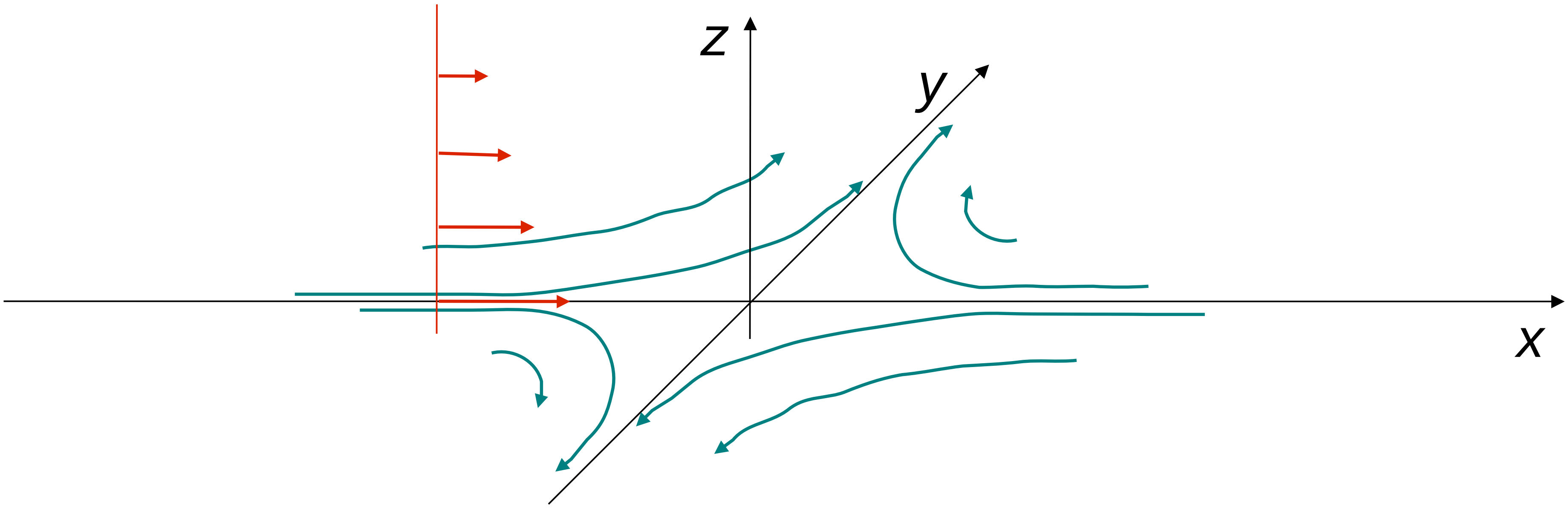
Generation argued to be well simulated, yet simulations sensitive to resolution



O'Sullivan & Dunkerton 1995
(Bush & Peltier 1995)
Zhang 2004, Plougonven & Snyder 2007

On the occurence in jet exit region

Propagation of a gravity wave in a deformation flow + vertical shear :



$$U(x,z) = -\alpha\, x + \gamma\, z\,,$$
$$V(y,z) = \alpha\, y + \beta\, z\,,$$

Badulin & Shrira 1993, **Bühler & McIntyre, 2005**

$$k = k_0\, e^{\alpha\, t}\,,$$

$$l = l_0\, e^{-\alpha\, t}\,,$$

$$m = m_0 + \frac{\gamma}{\alpha} k_0\, (1 - e^{\alpha\, t}) \;+\; \frac{\beta}{\alpha} l_0\, (e^{-\alpha\, t} - 1)$$

'Wave-capture' (Buhler & McIntyre 2004, Badulin & Shrira 1993)

IGW packet behaving like passive tracer:

- **phaselines align with extension axis**

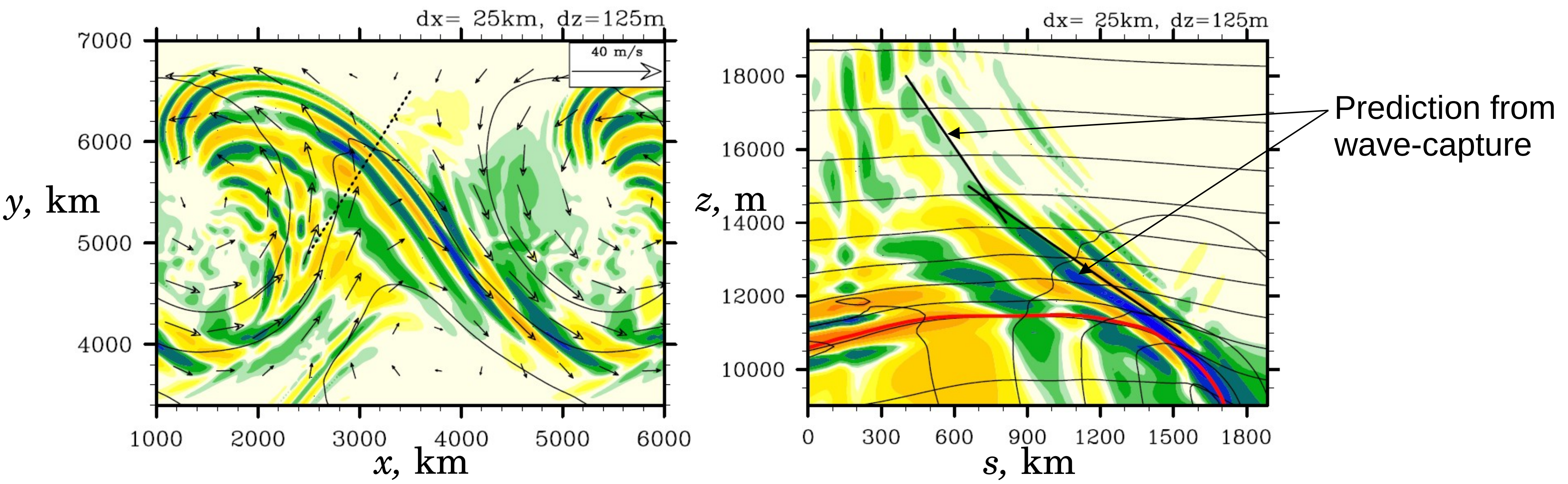
- **wavelengths decrease** exponentially

- 3D orientation (= **intrinsic frequency**) given by large-scale flow:

$$\frac{\lambda_H}{\lambda_z} \longrightarrow \frac{|\partial_z U|}{|\partial_x U|}$$

Badulin & Shrira 1993, **Bühler & McIntyre, 2005**

On the occurence in jet exit region

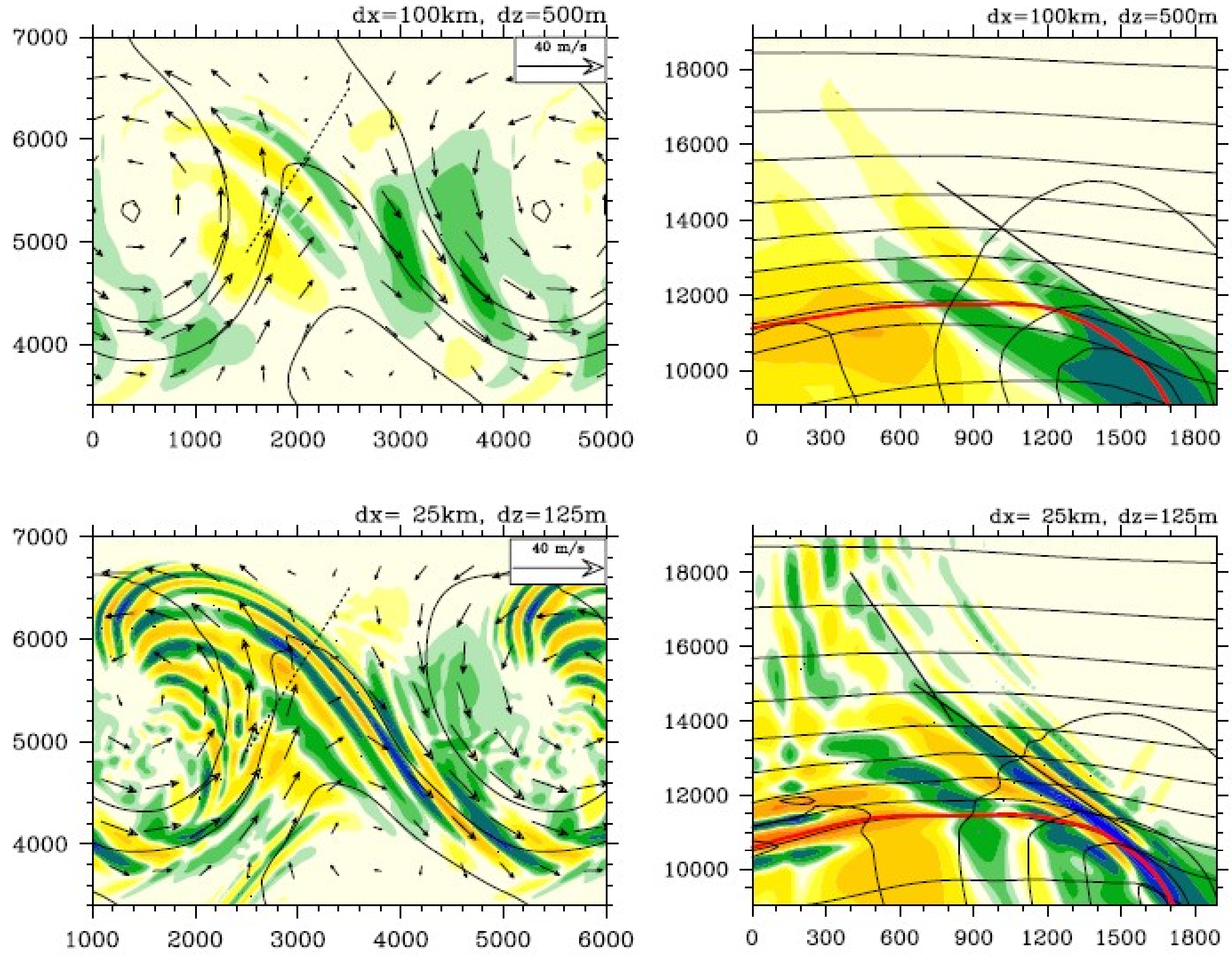


Horizontal cross-section of the divergence at z=11 km

Vertical cross-section of the divergence

Plougonven & Snyder, 2005, 2007

On sensitivity to resolution

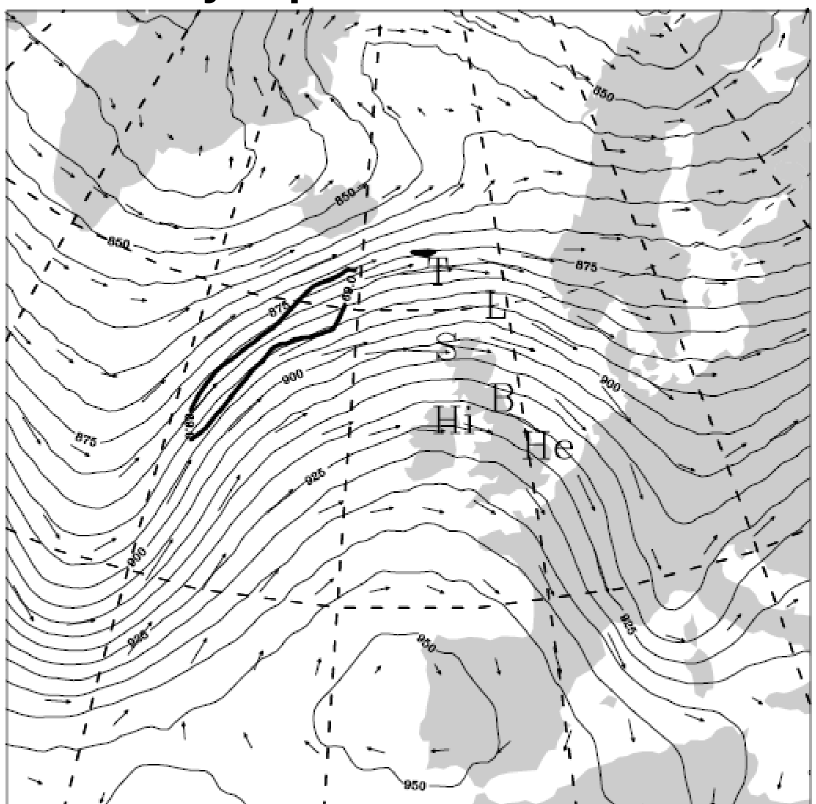


Sensitive to resolution, i.e. Simulations not converged numerically
But **location, orientation and intrinsic frequency are insensitive,** because they are **determined by the large-scale flow**

On the ability of NWP models to describe GW

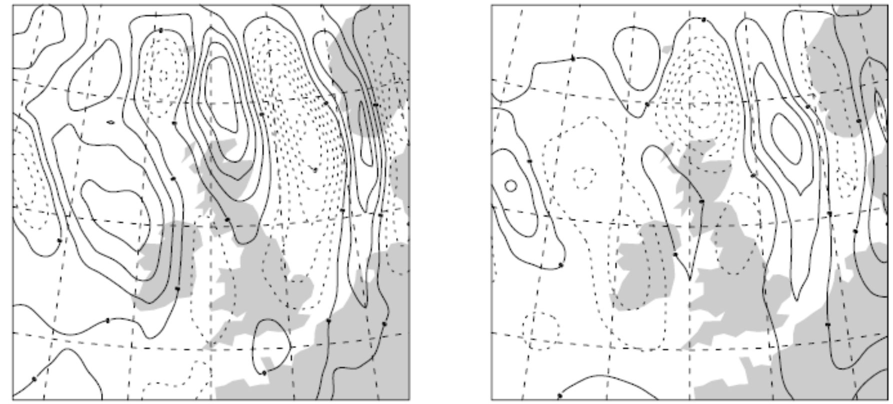
Case study **comparing IGW described by ECMWF and by 18 radiosondes** from FASTEX (1997)

Synoptic situation



Jet streak (– 69 m/s isotach) approaching a ridge of geopotential (300 hPa)

ECMWF IGW

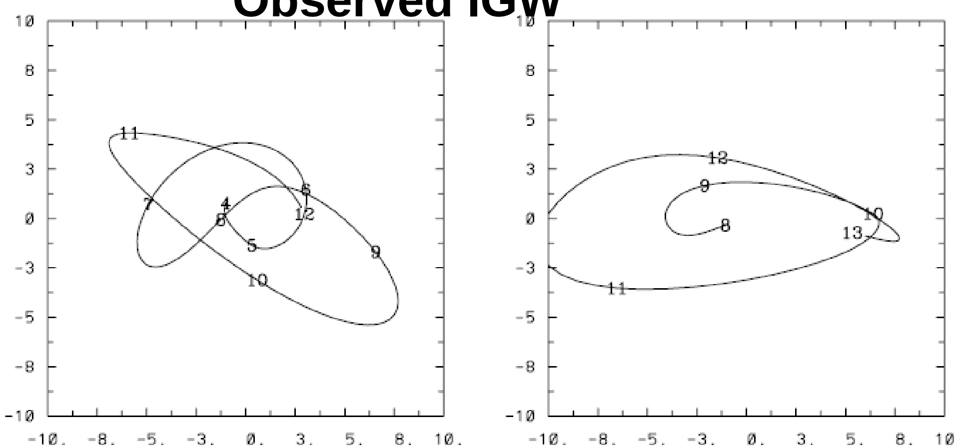


c) Divergence, Feb. 06, 00GMT

d) θ' , Feb. 06, 00GMT

ECMWF described IGW at the right time, right location, right intrinsic frequency and horizontal orientation

Observed IGW



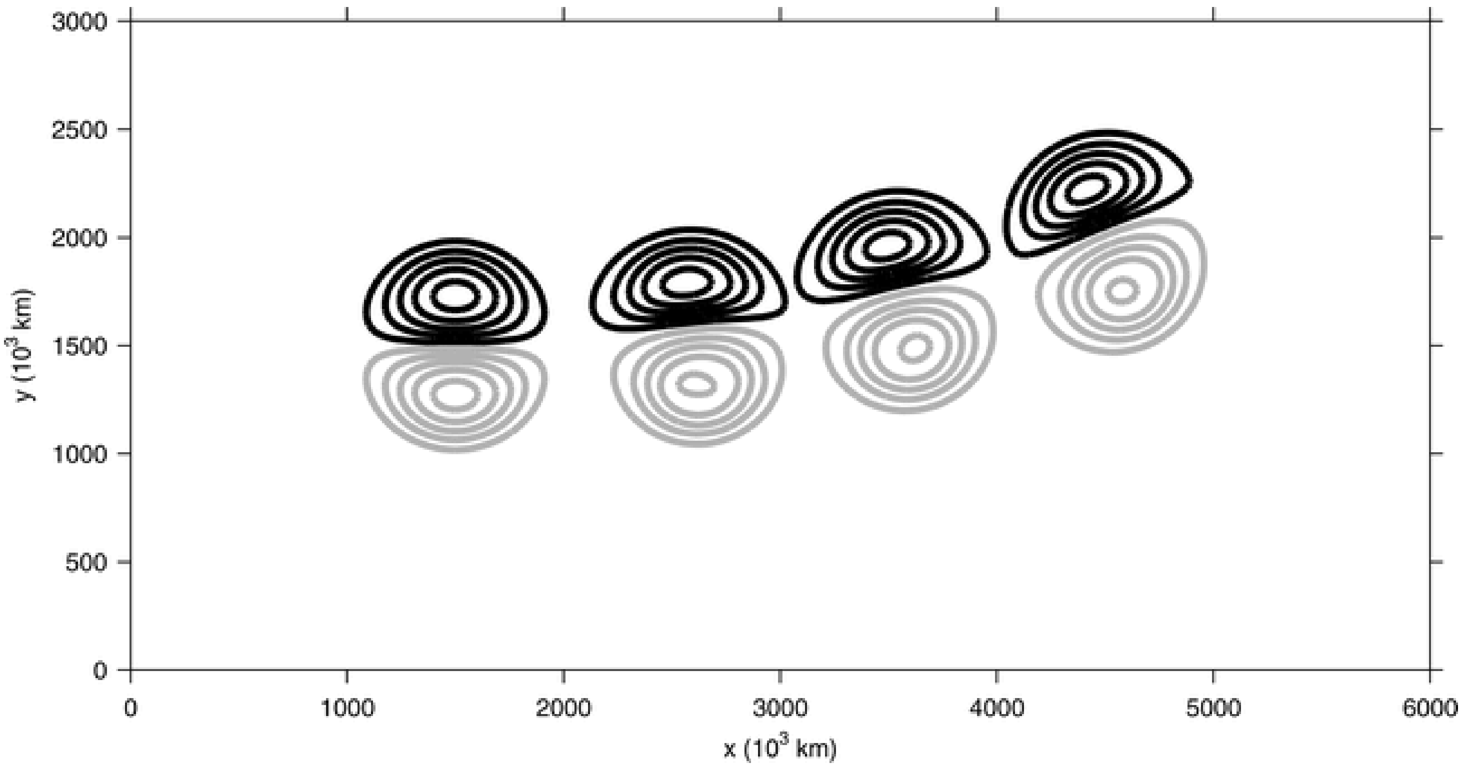
a) Hillsbor., 5/2, 11.15

b) Lerwick, 5/2, 17.24

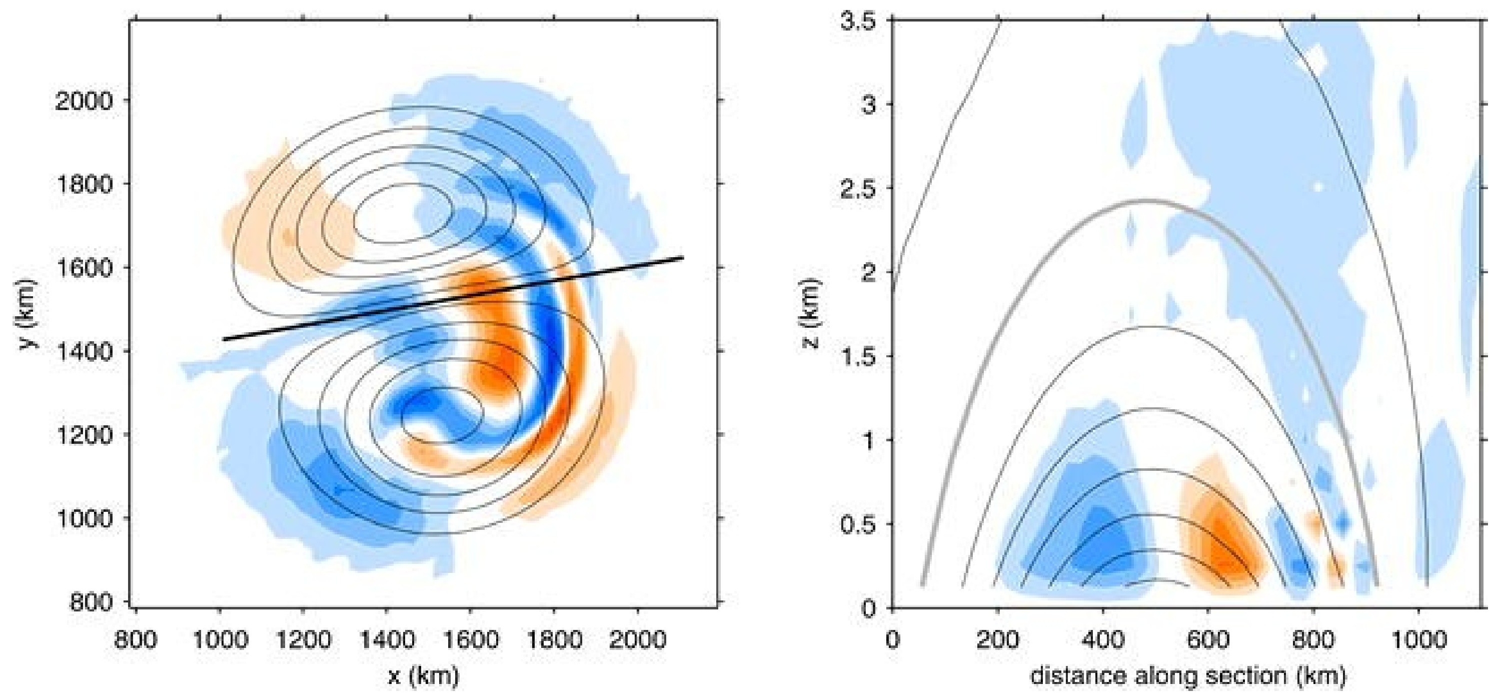
Plougonven & Teitelbaum, 2003

Simpler model for a jet streak: a dipole

Dipole trajectory over 40 days :



Stationary GW packet traveling with the dipole :



Van Tuyl and Young 1982

Snyder et al 2007, 2009

Interpretation

Mechanism for the generation:

waves are **<u>small perturbations</u>** to a dipole that is nearly balanced

1. **Separate** the flow into a balanced part and a perturbation

$$u = \overline{u} + u'$$

Balanced approx. of dipole (for $\overline{u}$)

Small perturbations: balanced corrections + IGW (for u')

2. **Linearize** about the balanced part

3. Follow **dynamics of perturbations**
   homogeneous (instability?)
   forced

$$\partial_t \overline{u} + \partial_t u' \; + \overline{\mathbf{u}} \cdot \nabla \overline{u} + \overline{\mathbf{u}} \cdot \nabla u'$$

$$+ \mathbf{u}' \cdot \nabla \overline{u} + \mathbf{u}' \cdot \nabla u' \; - f \, \overline{v} - f \, v' + \partial_x \, \overline{\phi} + \partial_x \, \phi' = 0 \; ,$$

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f \, v' + \partial_x \, \phi' = \mathcal{F}_u + \mathcal{O}(u'^2) \; ,$$

$$\text{where} \quad \mathcal{F}_u = - \left(\partial_t \overline{u} + \overline{\mathbf{u}} \cdot \nabla \overline{u} - f \, \overline{v} + \partial_x \, \overline{\phi} \right) \; .$$

$$\partial_t \overline{u} + \partial_t u' + \overline{\mathbf{u}} \cdot \nabla \overline{u} + \overline{\mathbf{u}} \cdot \nabla u'$$

$$+ \mathbf{u}' \cdot \nabla \overline{u} + \mathbf{u}' \cdot \nabla u' - f\,\overline{v} - f\,v' + \partial_x\,\overline{\phi} + \partial_x\,\phi' = 0\ ,$$

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\,v' + \partial_x\,\phi' = \mathcal{F}_u + \mathcal{O}(u'^2)\ ,$$

$$\text{where} \quad \mathcal{F}_u = -\left(\partial_t \overline{u} + \overline{\mathbf{u}} \cdot \nabla \overline{u} - f\,\overline{v} + \partial_x\,\overline{\phi}\right)\ .$$

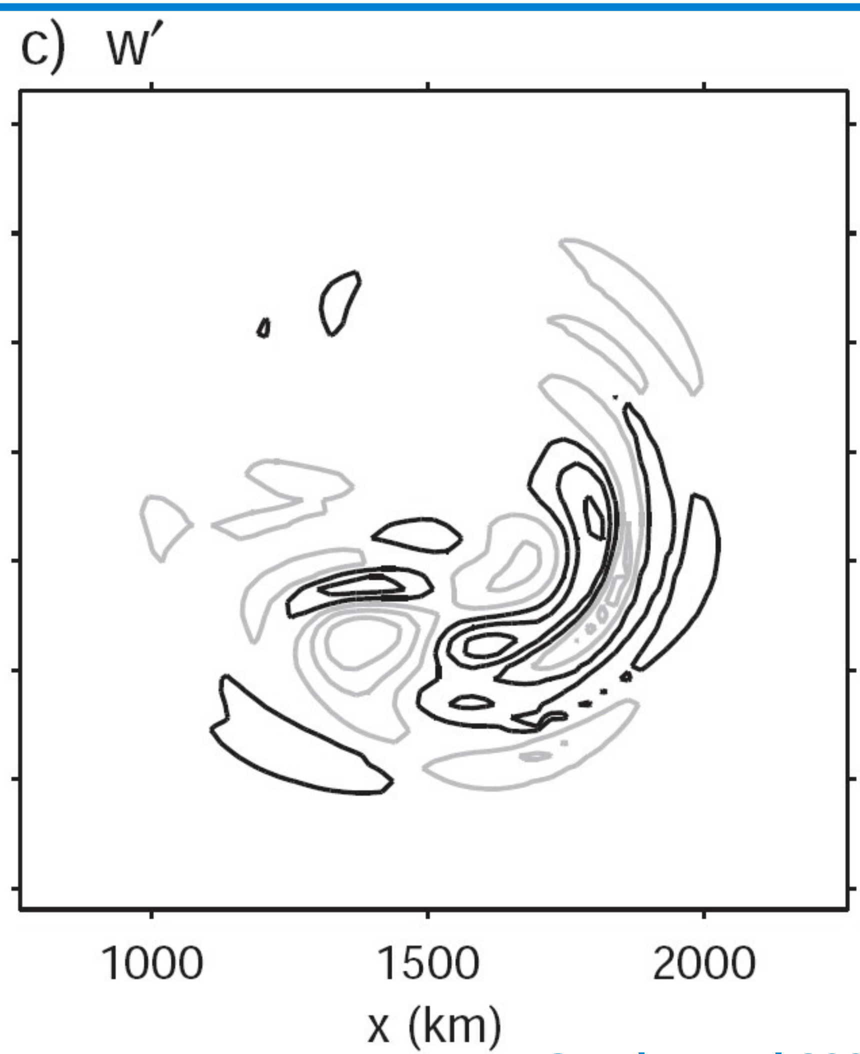
Homogeneous solutions :

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\, v' + \partial_x \phi' = 0$$

No growth fast enough to explain waves as the result of an instability,

BUT:

structures that emerge in *w* very similar to IGW:

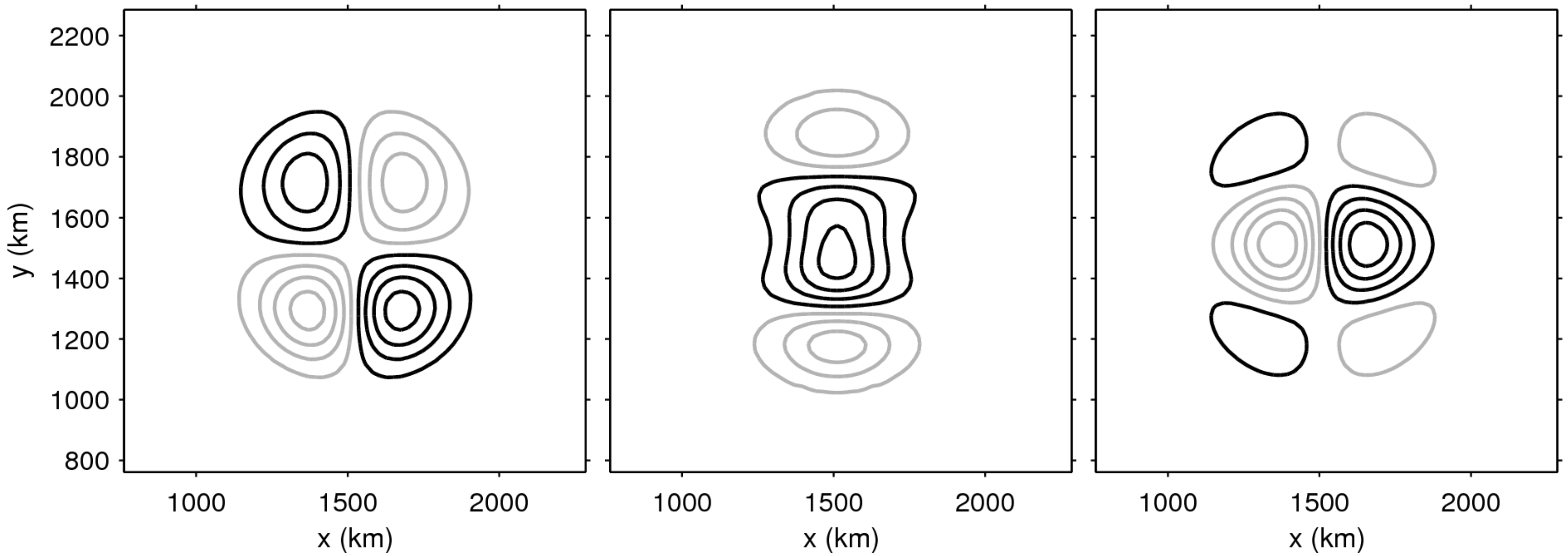


Snyder et al 2009

Forced solutions :

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\, v' + \partial_x \phi' = \mathcal{F}_u$$

Forcing terms (known from the QG dipole) :



NB all **the forcing is large scale**, and does not distinguish the front and rear

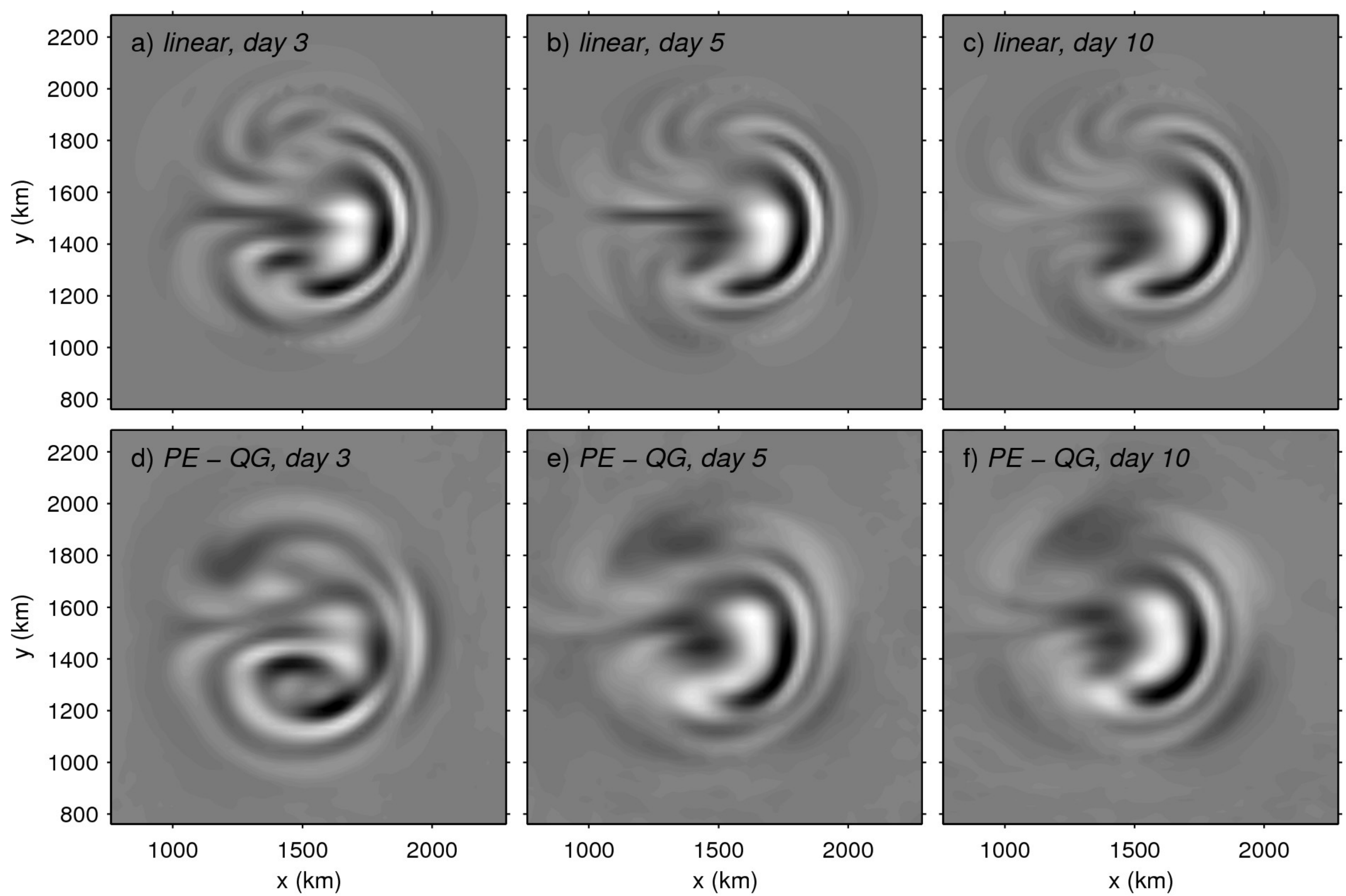
Snyder et al 2009

Forced solutions :

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\, v' + \partial_x \phi' = \mathcal{F}_u$$

W' predicted by linear, forced calculations:

good qualitative agreement



1

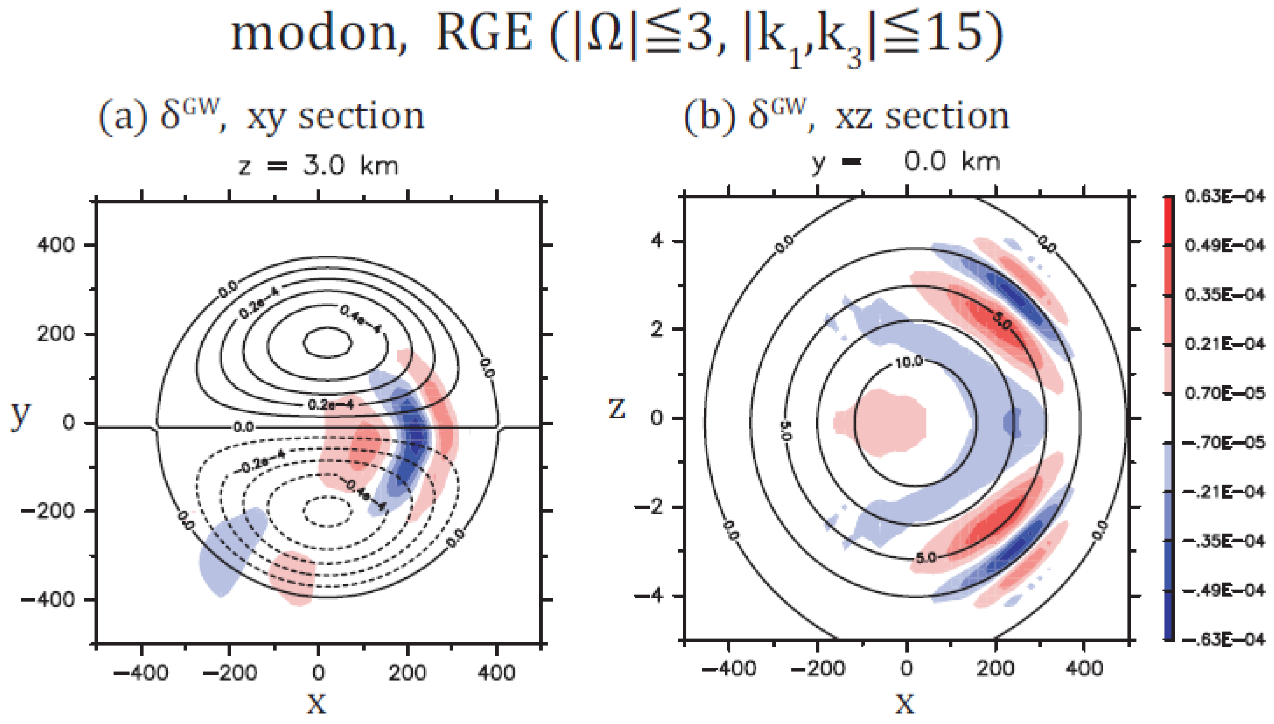
Snyder et al 2009

Viudez 2007, 2008, Wang et al 2009, Wang et al 2010, Wang & Zhang 2010

Emission described by renormalization group theory

Emission in dipole revisited using **renormalization group theory**

→ interpretation of generation mechanism
→ interaction of the waves and the dipole



Yasuda, Sato & Sugimoto, 2014a,b

Toward more realistic flows...

real case simulations in parallel of balloon observations

Superpressure balloons

– Constant volume → ispoycnic
→ quasi-Lagrangian
→ **intrinsic frequencies**

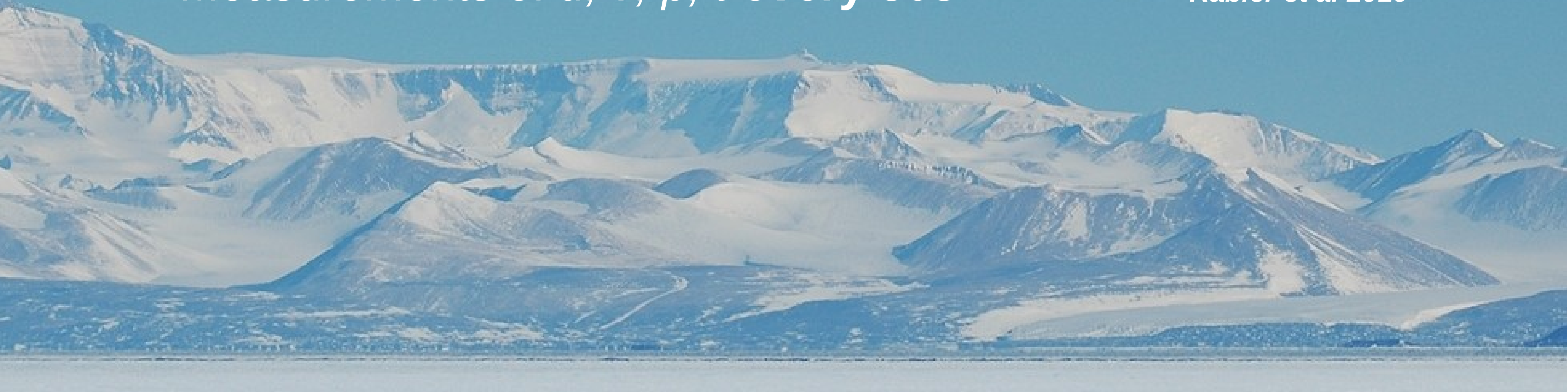
– Drift in lower stratosphere (~70 – 50 hPa)
2 months flights on average

VORCORE: Sept. 2005 – Feb. 2006, 27 balloons
Measurements of *u, v, p, t* every 15 min.

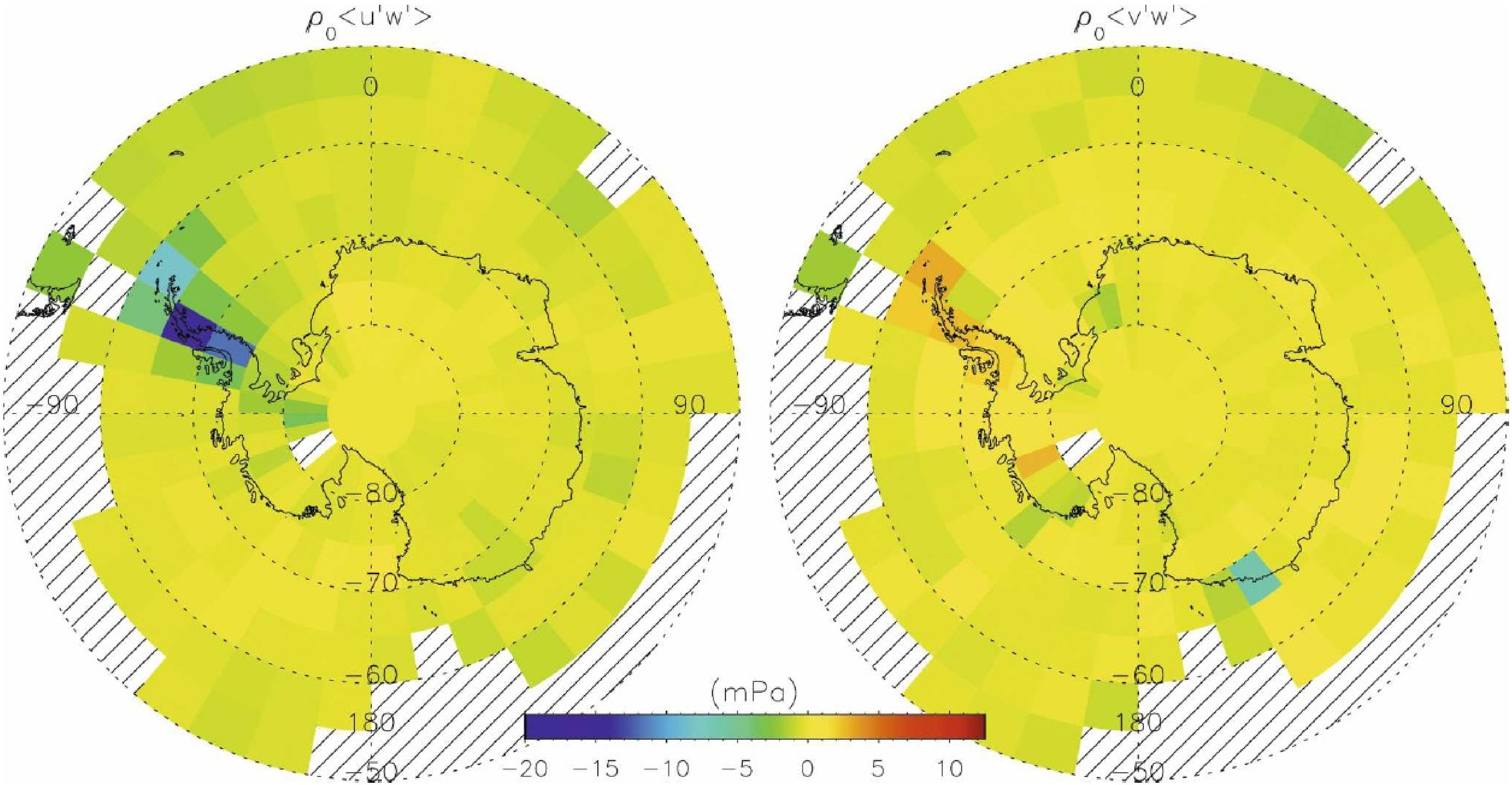
Hertzog et al 2007, 2008

Concordiasi: Sept. 2010 – Jan. 2011, 19 balloons
Measurements of *u, v, p, t* **every 30s**

Rabier et al 2010



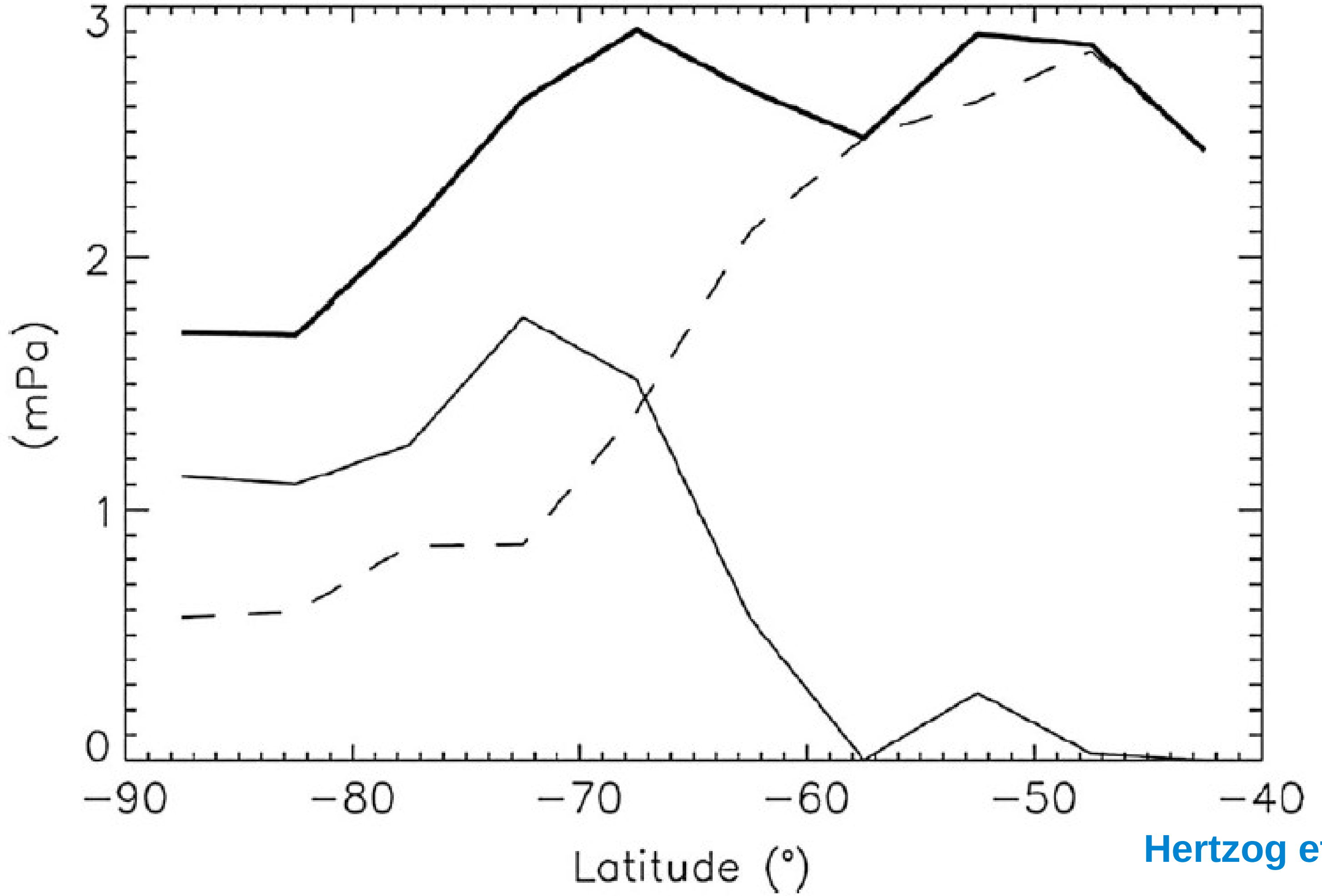
Momentum fluxes estimated from VORCORE
(2005, measurements every 15 min.)



Vincent et al 2007, **Hertzog et al 2008**

Orographic hotspot comes out conspicuously, but...

Zonally integrated contributions over oceans (- -), over orography (–) to the total (**–**)



Hertzog et al 2008

3

Confirmation of the **importance of non-orographic gravity** waves for momentum fluxes into the middle atmosphere

Role in the late breakup of the Southern stratospheric polar vortex ?

McLandress et al 2012, Jewtoukoff et al 2015

Mesoscale simulations in parallel of VORCORE

Weather Research and Forecast (WRF) Model (Skamarock et al 2008)

Domain and resolution :

10 000 km x 10 000 km, *dx* = 20 km
up to 5 hPa with 120 levels

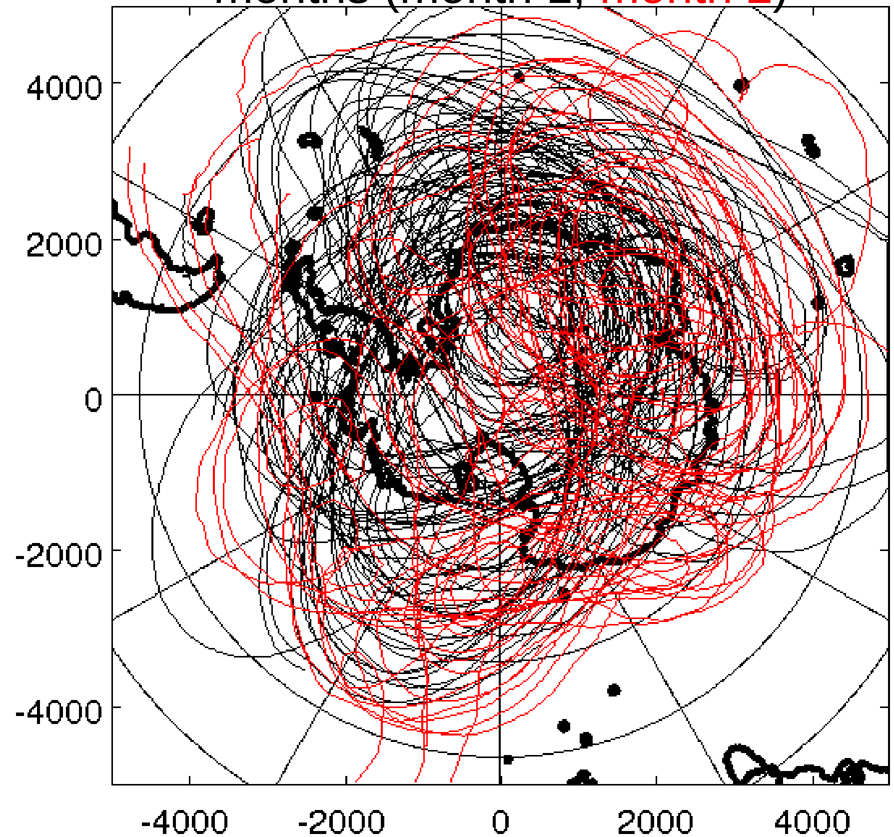
Time period :

October 21, 2005, 00:00UT

58 days

December 18, 2005, 00:00UT

Balloon trajectories for the 2 months (month 1, month 2)

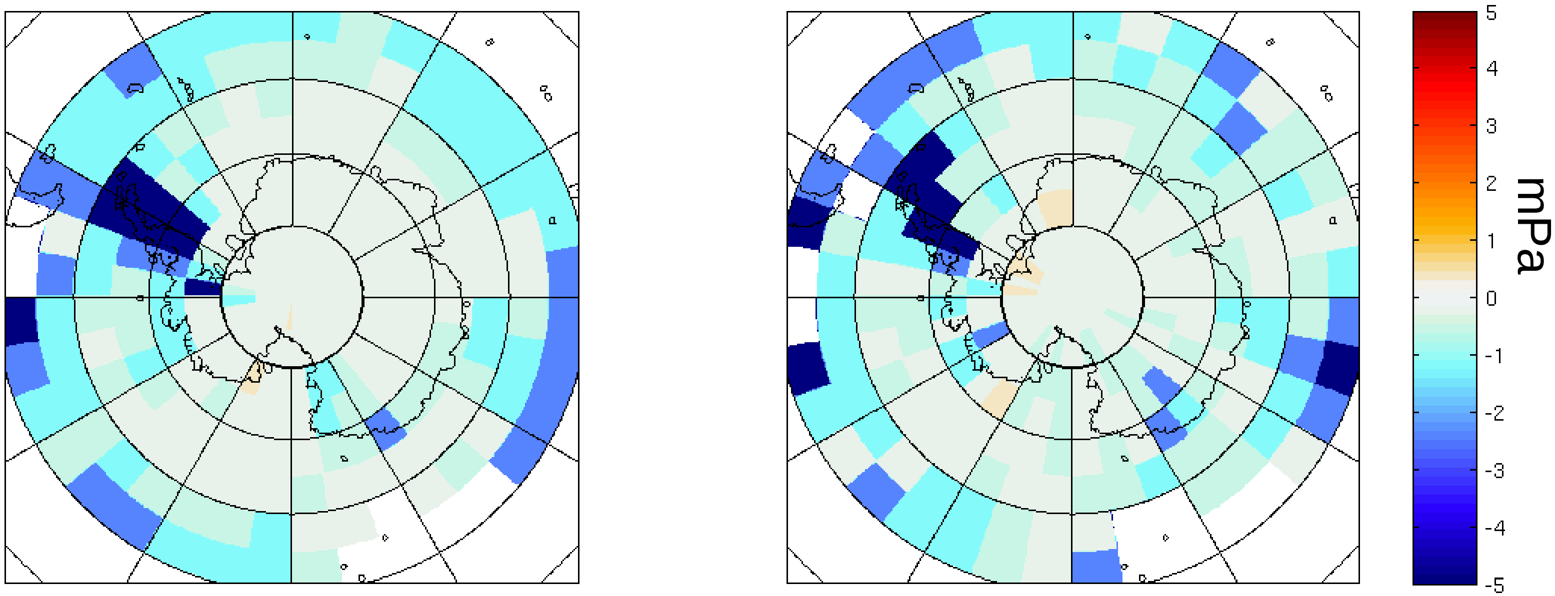


Plougonven et al 2010, 2013

Mesoscale simulations in parallel of VORCORE

Time-averaged momentum fluxes (<*ρ u' w'*>)**:**

Comparison of the mean zonal momentum fluxes in the simulations & observations

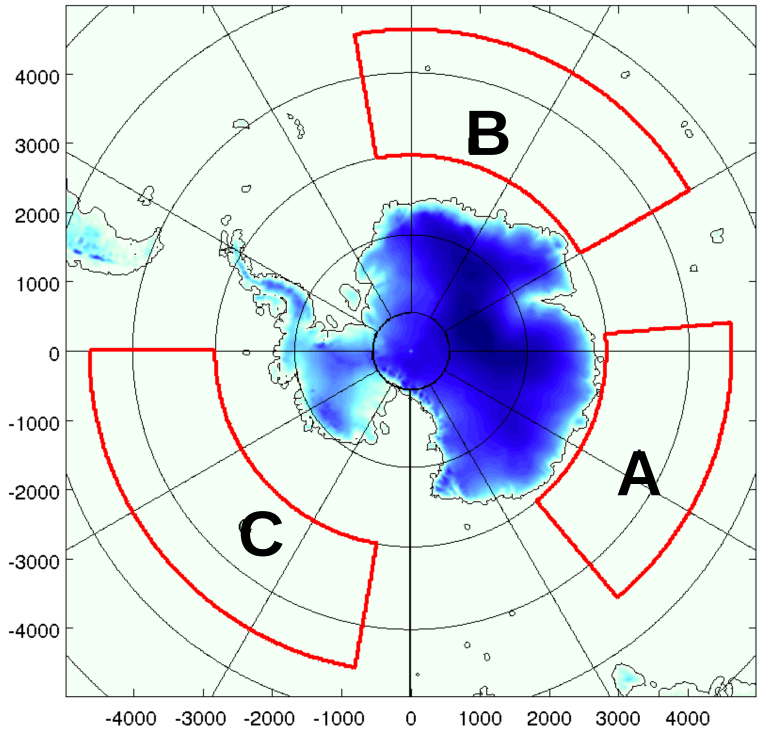


Good overall agreement,
Similar order of magnitude
- maximum over the Antarctic Peninsula
- **comparable structures and amplitude over the ocean**
(observed average : 0.83 mPa, simulated average : 0.67 mPa)

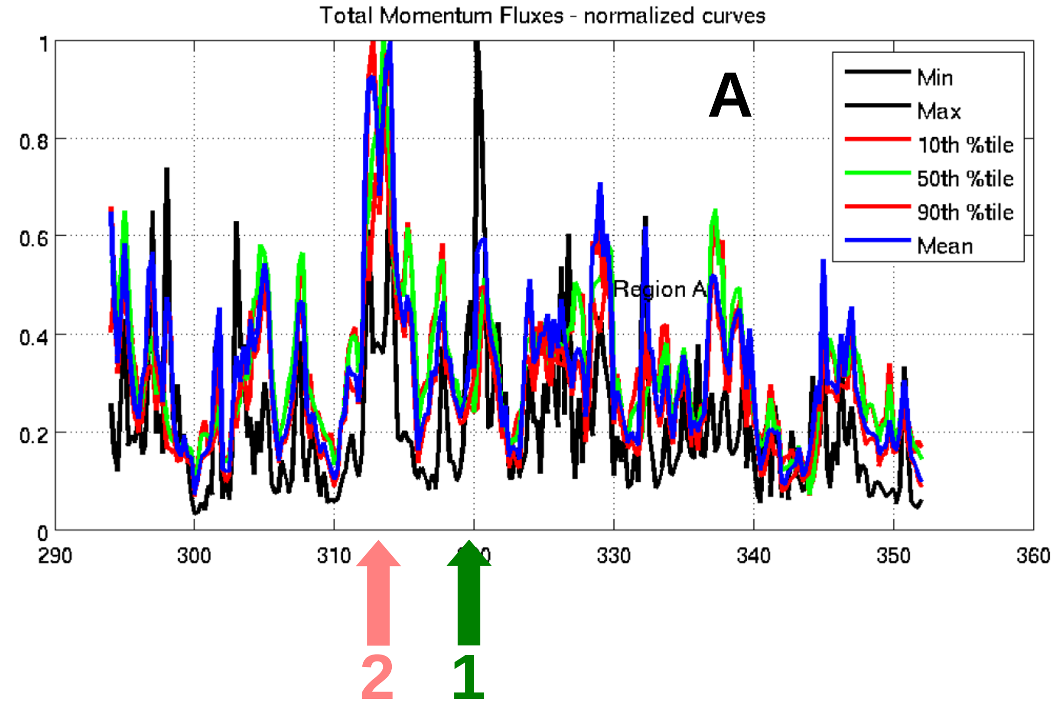
Case study

Choice of case studies :

1. Identify 3 regions where GW are non-orographic



2. Examine time series of mean momentum fluxes over each region



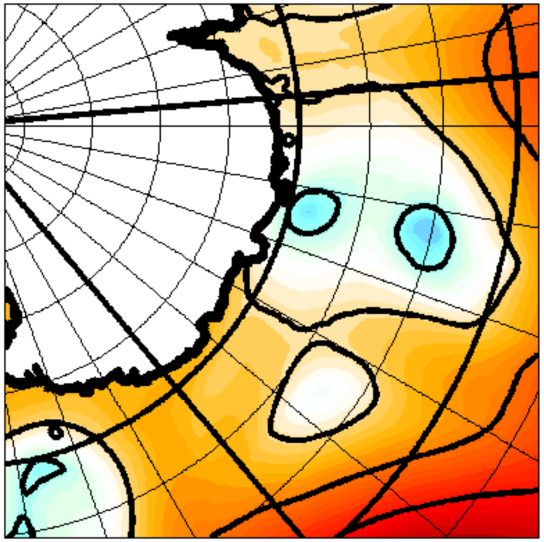
3. Choose case studies for intense events :

- **Case 1 : day 320**
- **Case 2 : day 313**
- **Case 3 : region C, day 296**

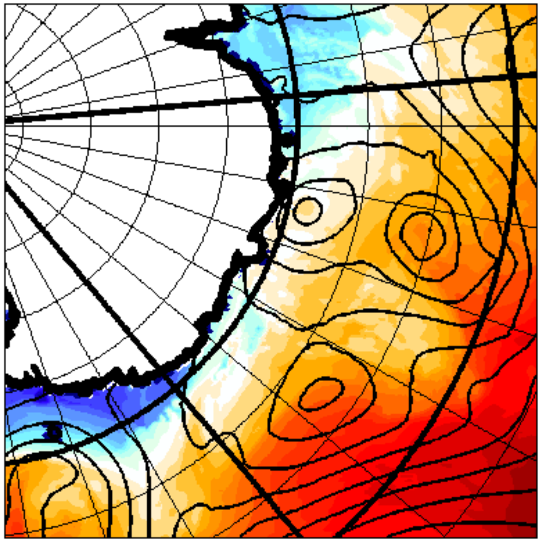
Plougonven et al 2015

Case study

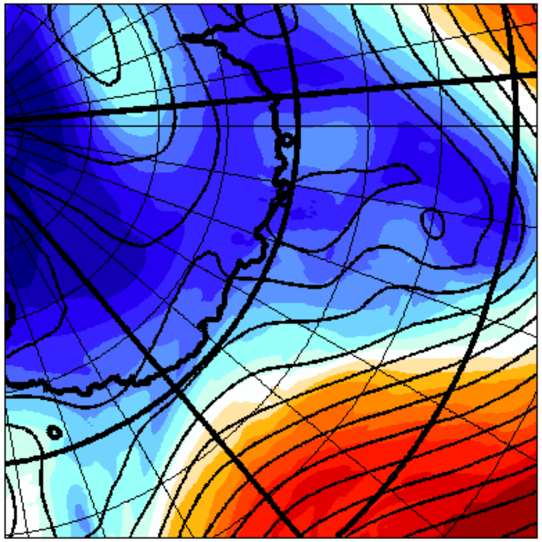
Meteorological situation – tropospheric flow



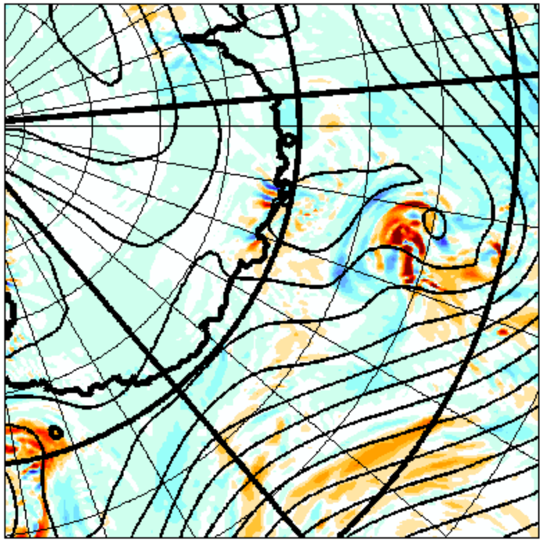
Surface pressure



Surface temperature (+ isobars)



Potential temperature at z=5 km (+ isobars)



Vertical velocity at z=5 km (+ isobars)

November 15, 2005, 18:00

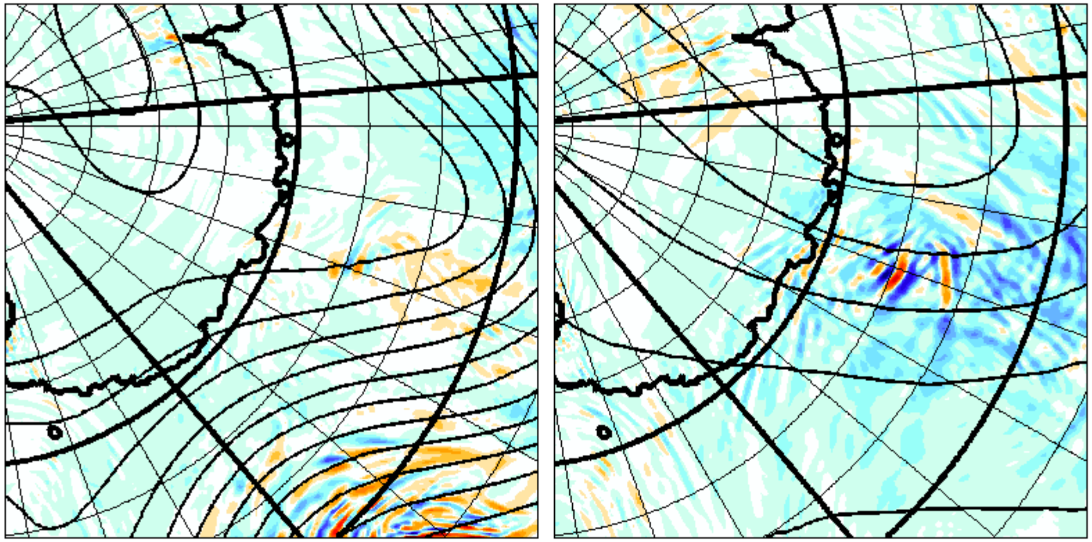
Case study

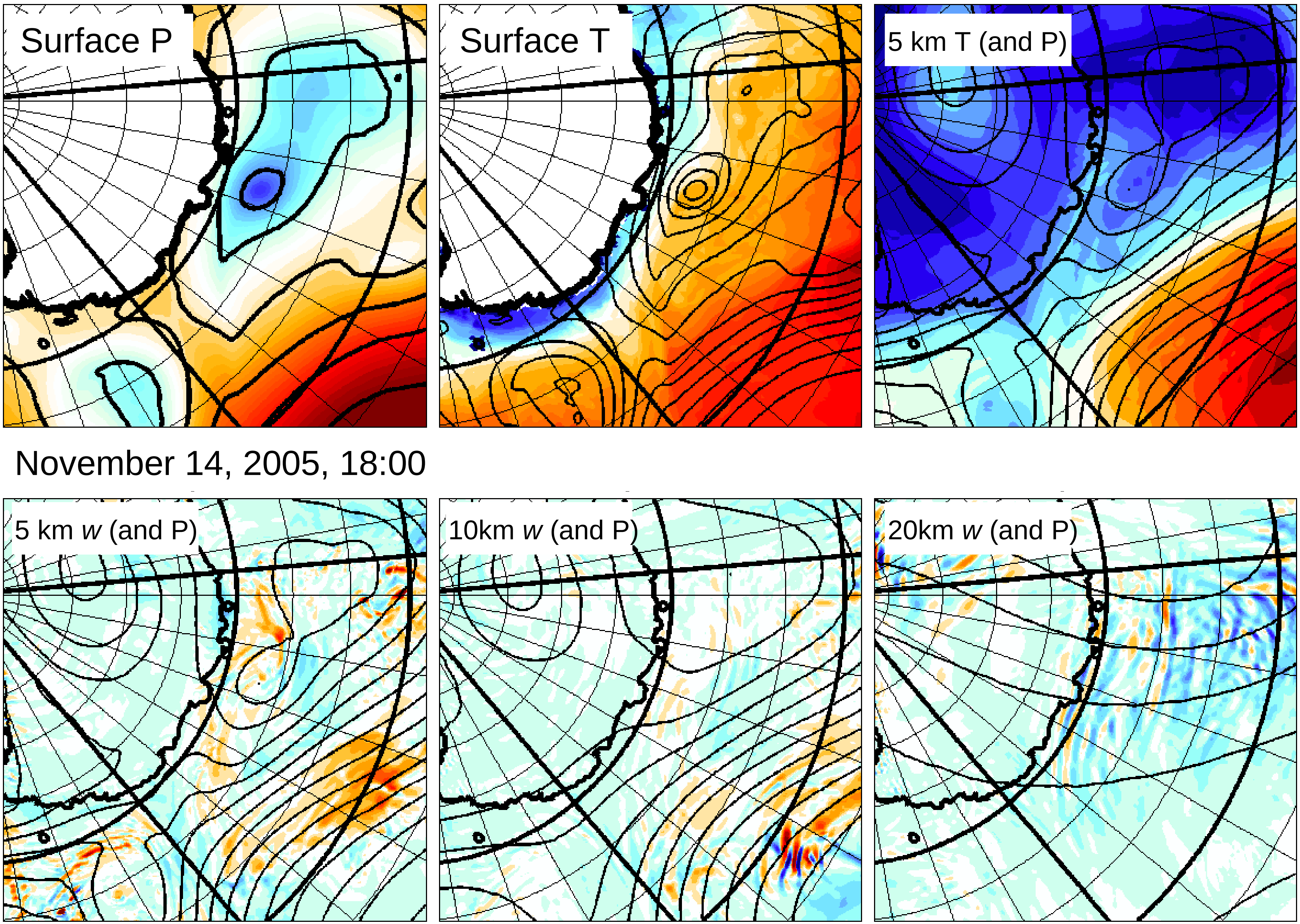
Stratospheric gravity waves

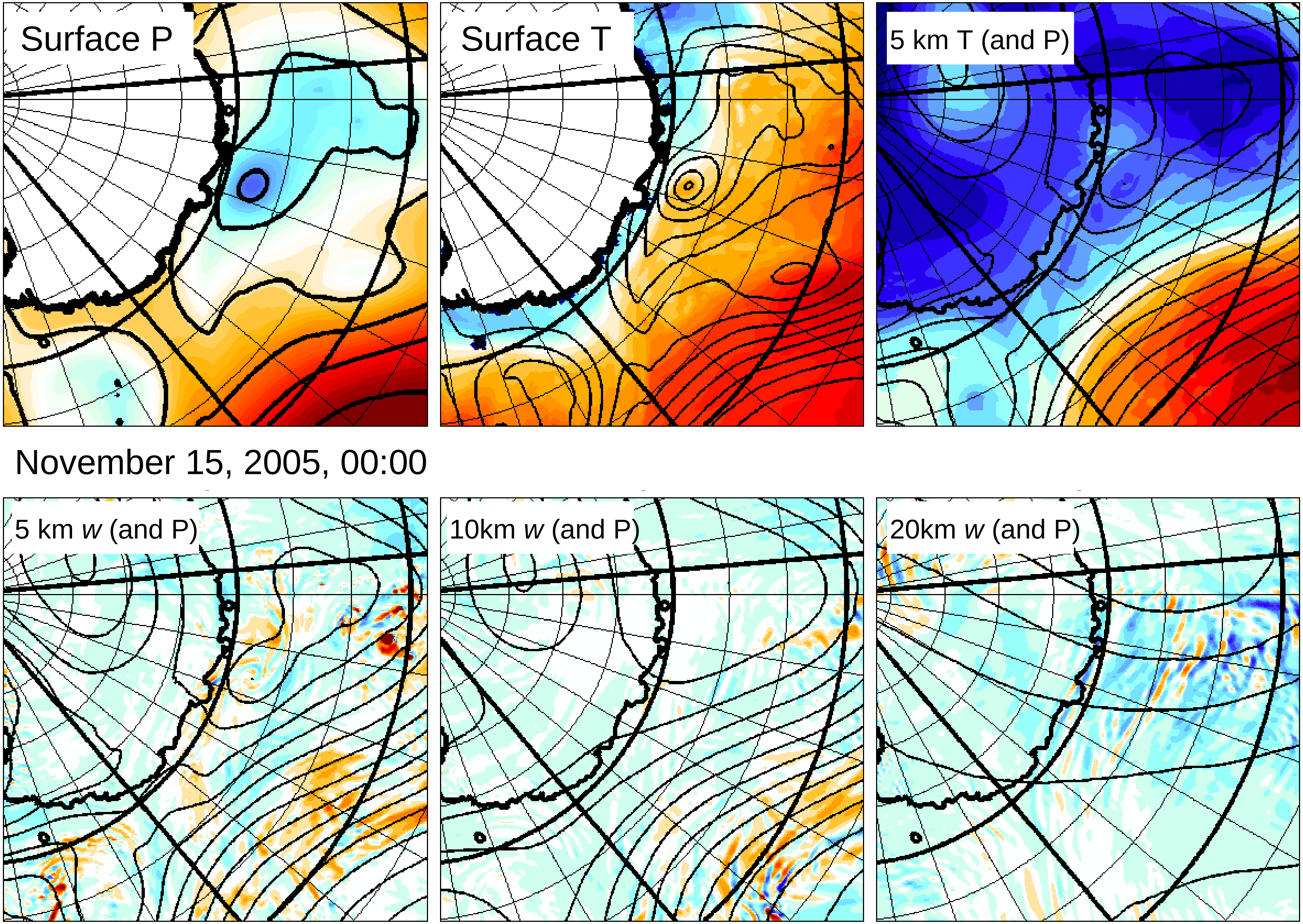
November 15, 2005, 18:00

Vertical velocity at z=10 km (+ isobars)

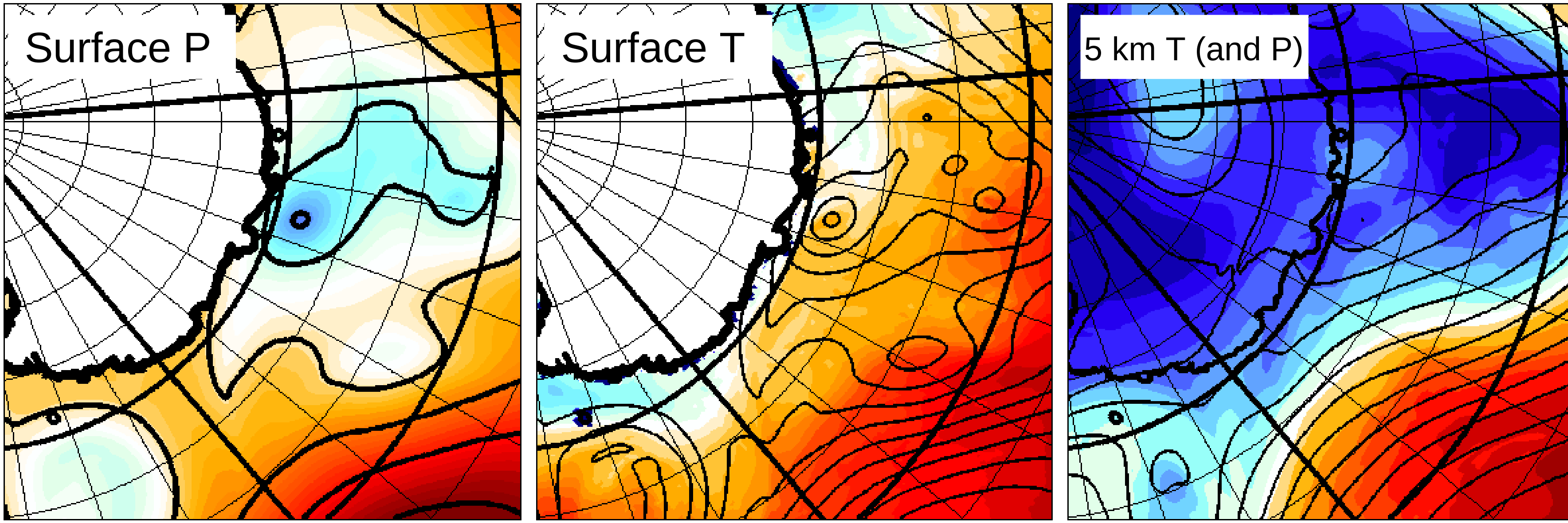
Vertical velocity at z=20 km (+ isobars)



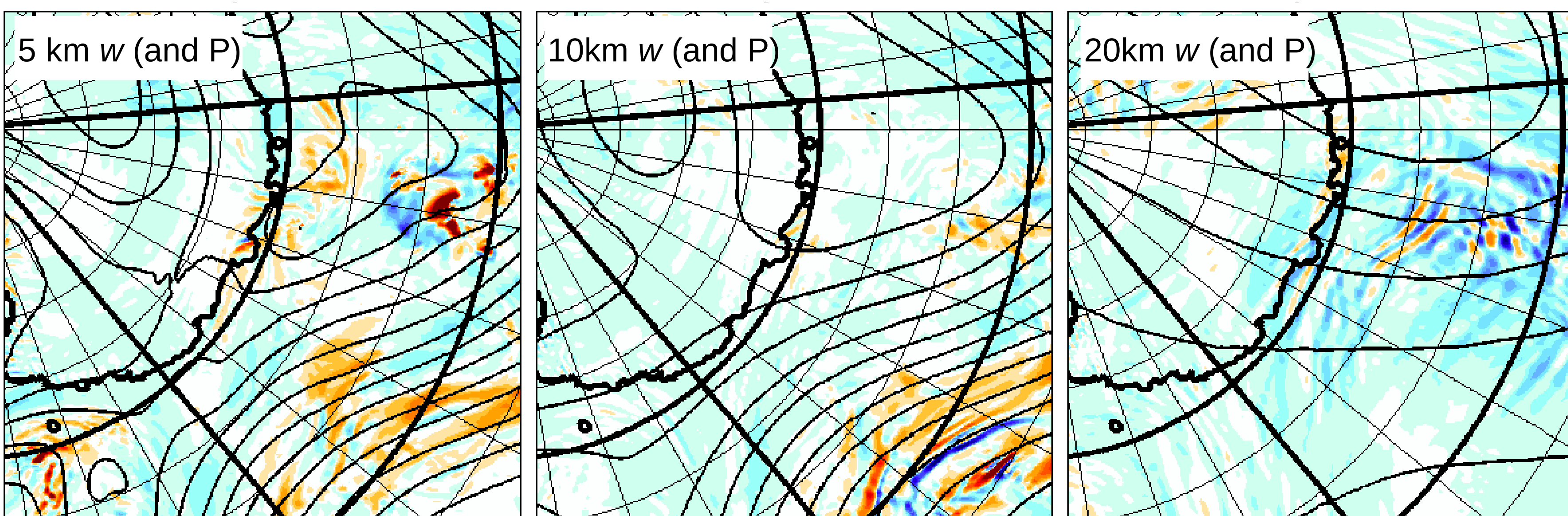

Surface P
Surface T
5 km T (and P)
November 14, 2005, 18:00
5 km w (and P)
10km w (and P)
20km w (and P)

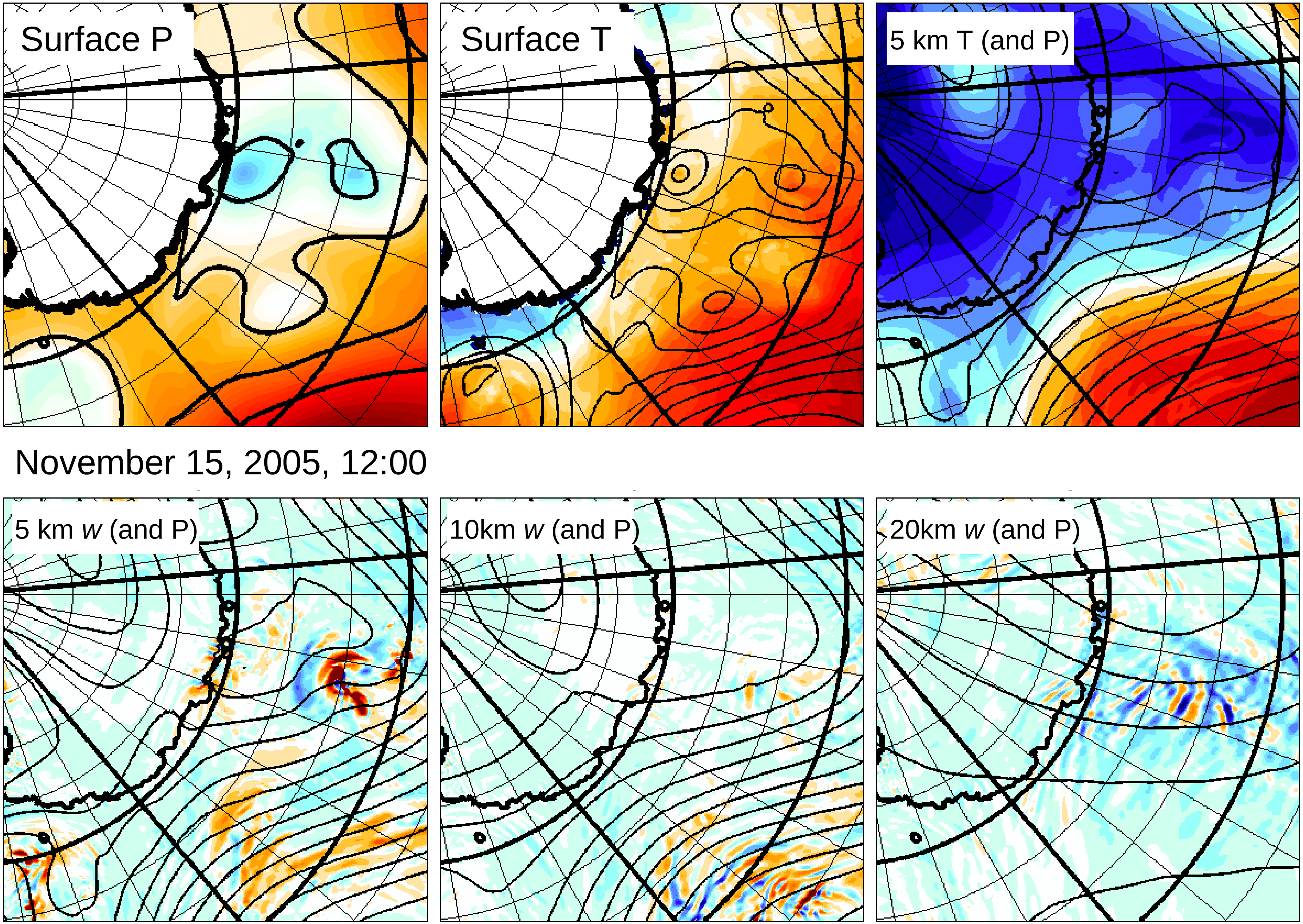


November 15, 2005, 00:00

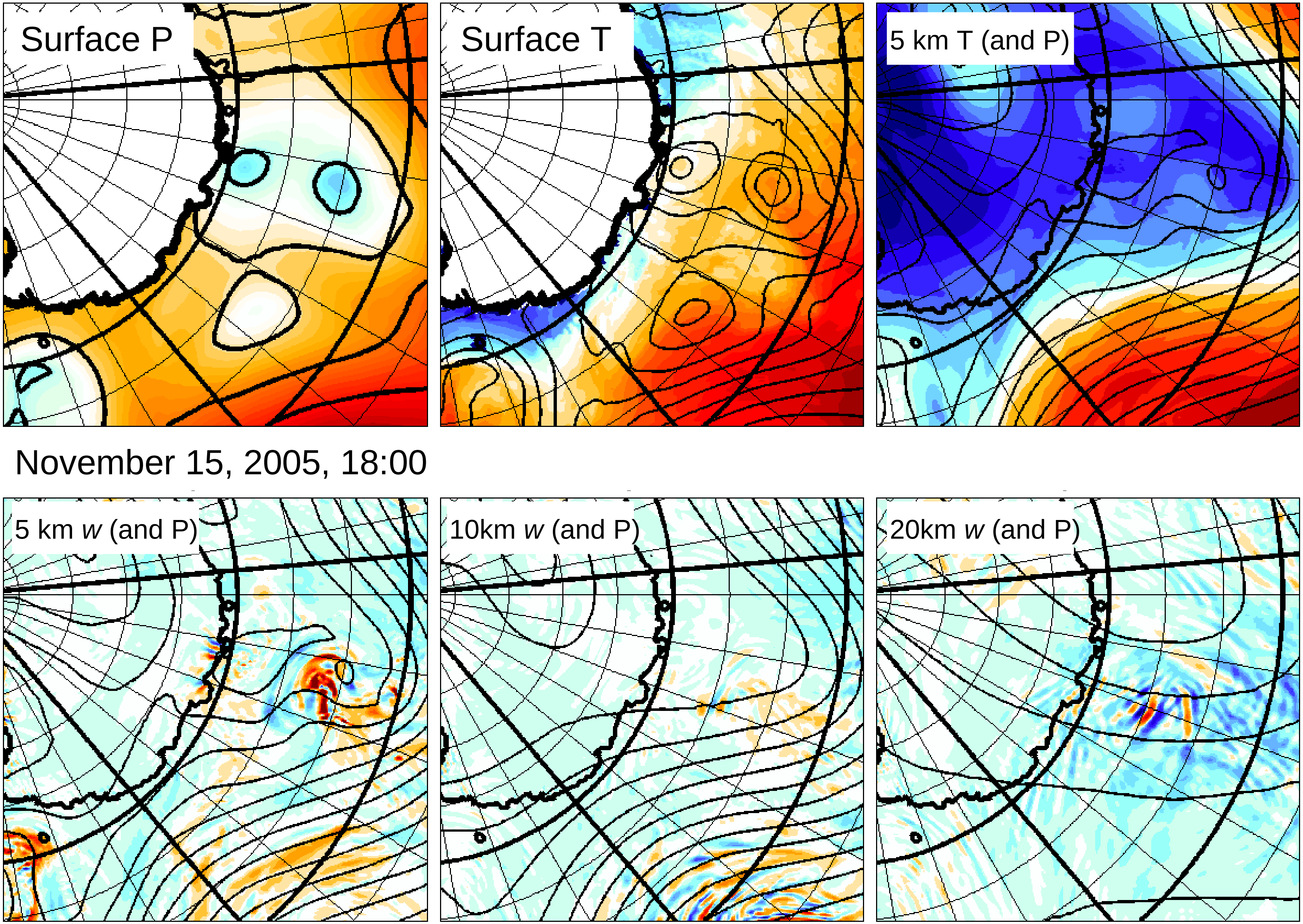


November 15, 2005, 06:00

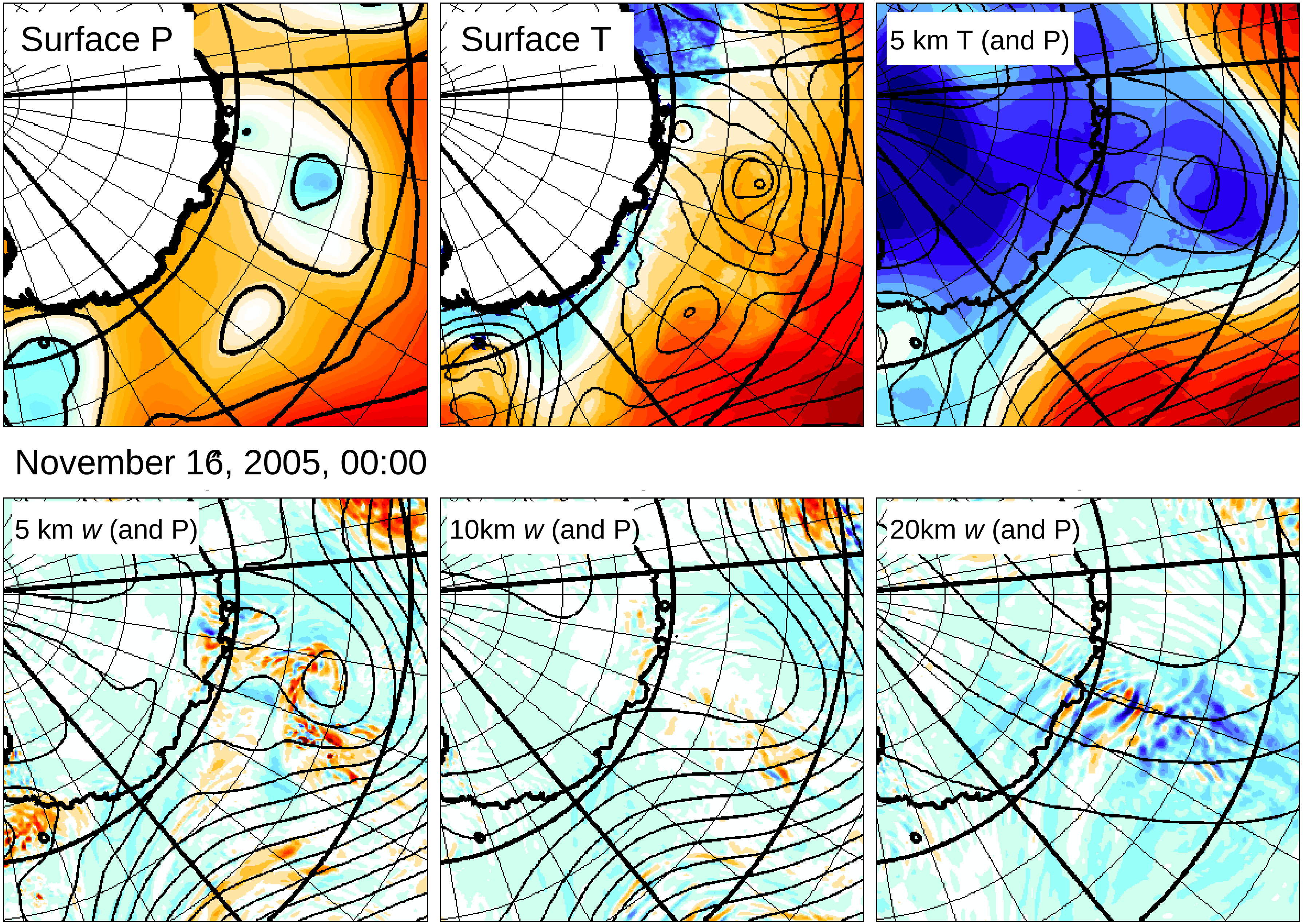




November 15, 2005, 12:00

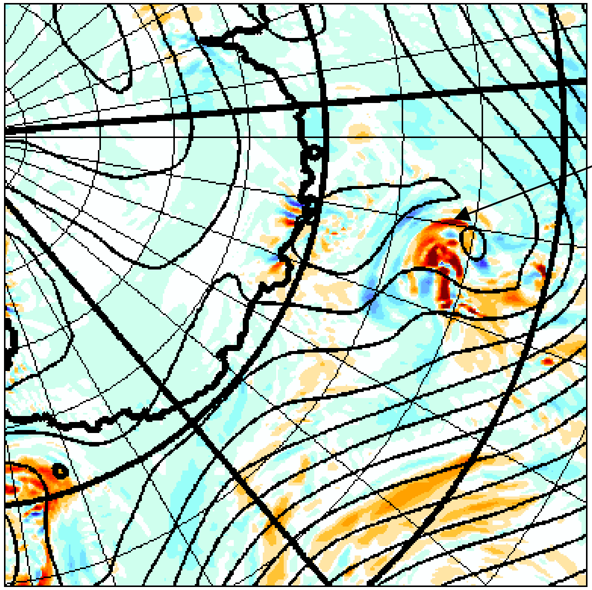


November 15, 2005, 18:00

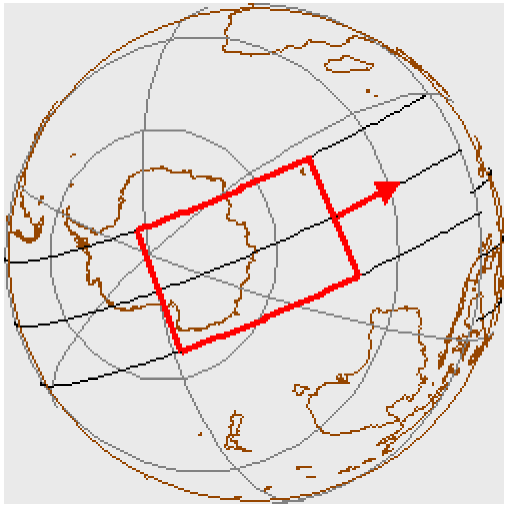

Surface P
Surface T
5 km T (and P)
November 16, 2005, 00:00
5 km *w* (and P)
10km *w* (and P)
20km *w* (and P)

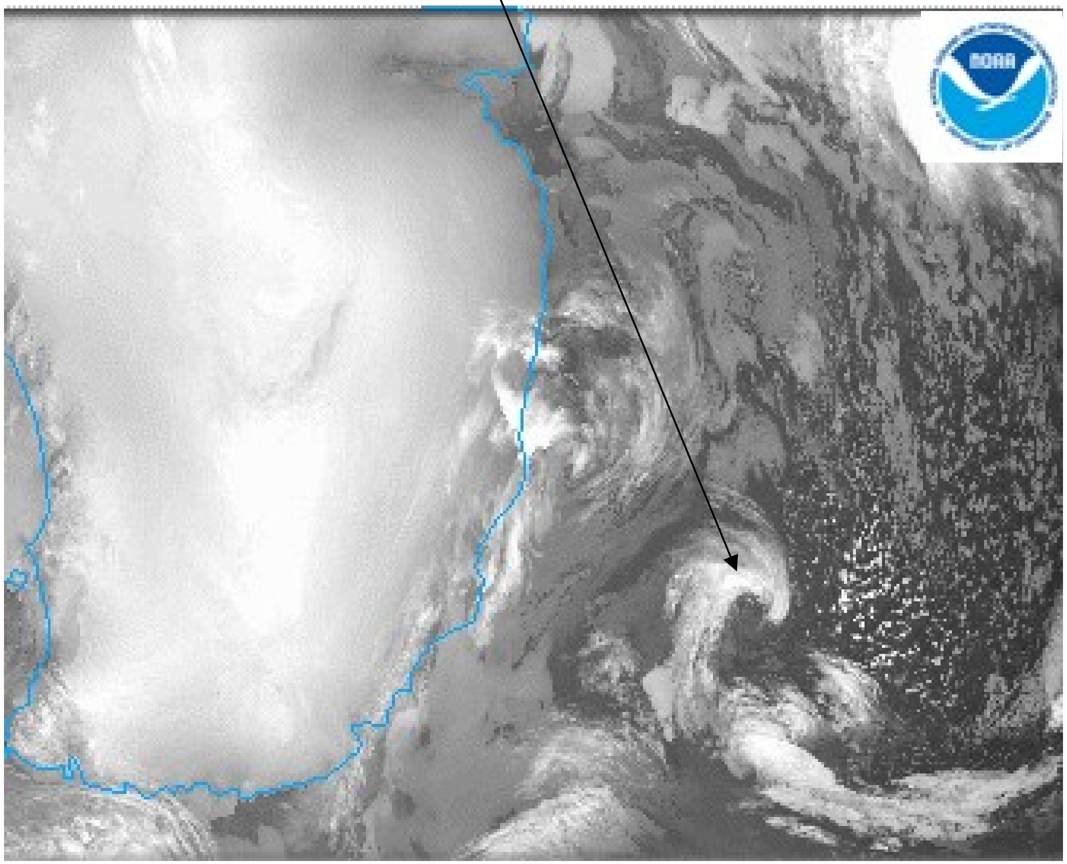
Validation with observations : clouds around polar low

w on Nov. 15, 18UT, z=5km



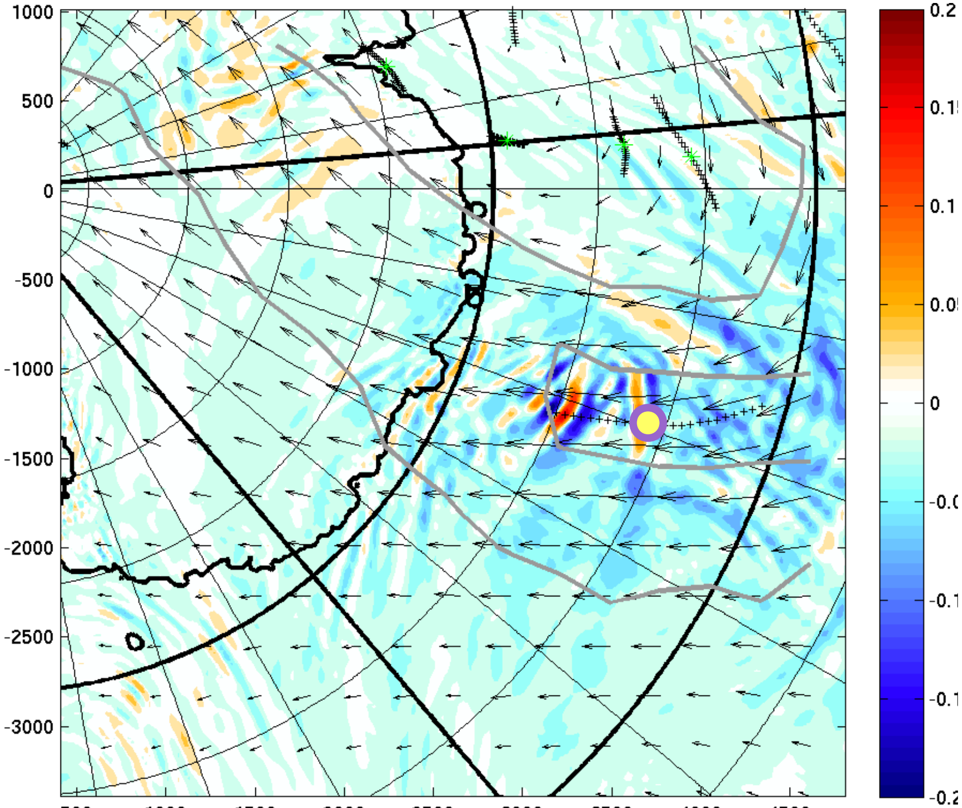
Satellite image from the Defense Meteorological Satellite Program (DMSP)





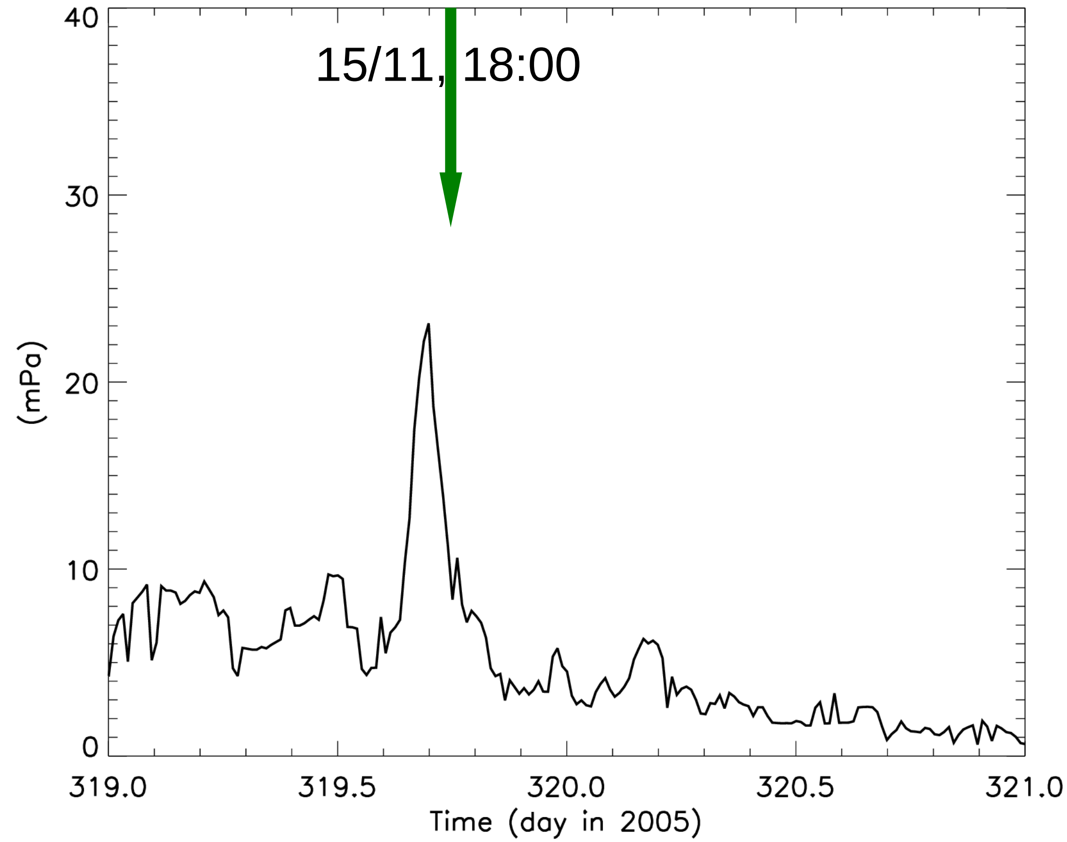
Validation with observations : gravity waves

W (and wind) at *z*=20 km, 15/11, 18:00

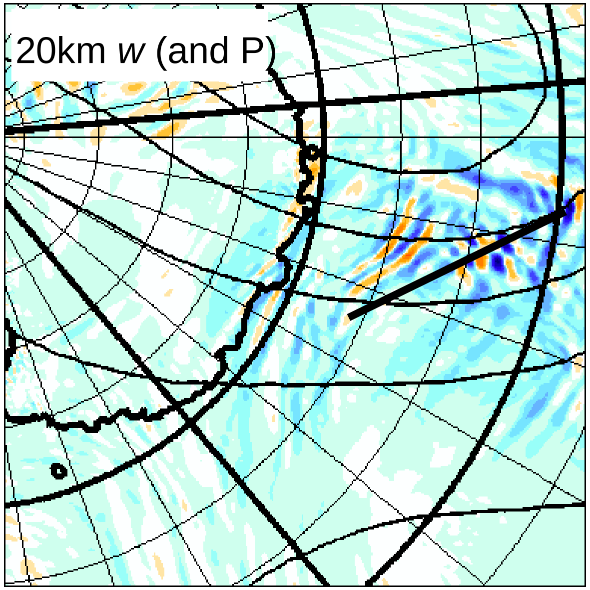


Balloon #3

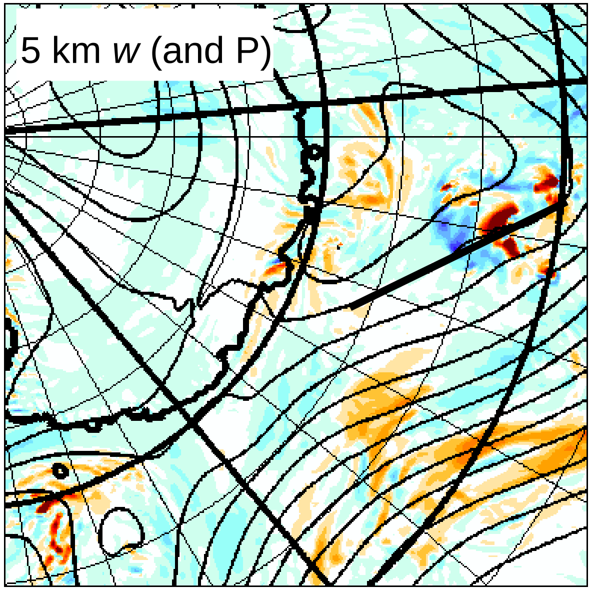
Momentum flux time series for balloon #3

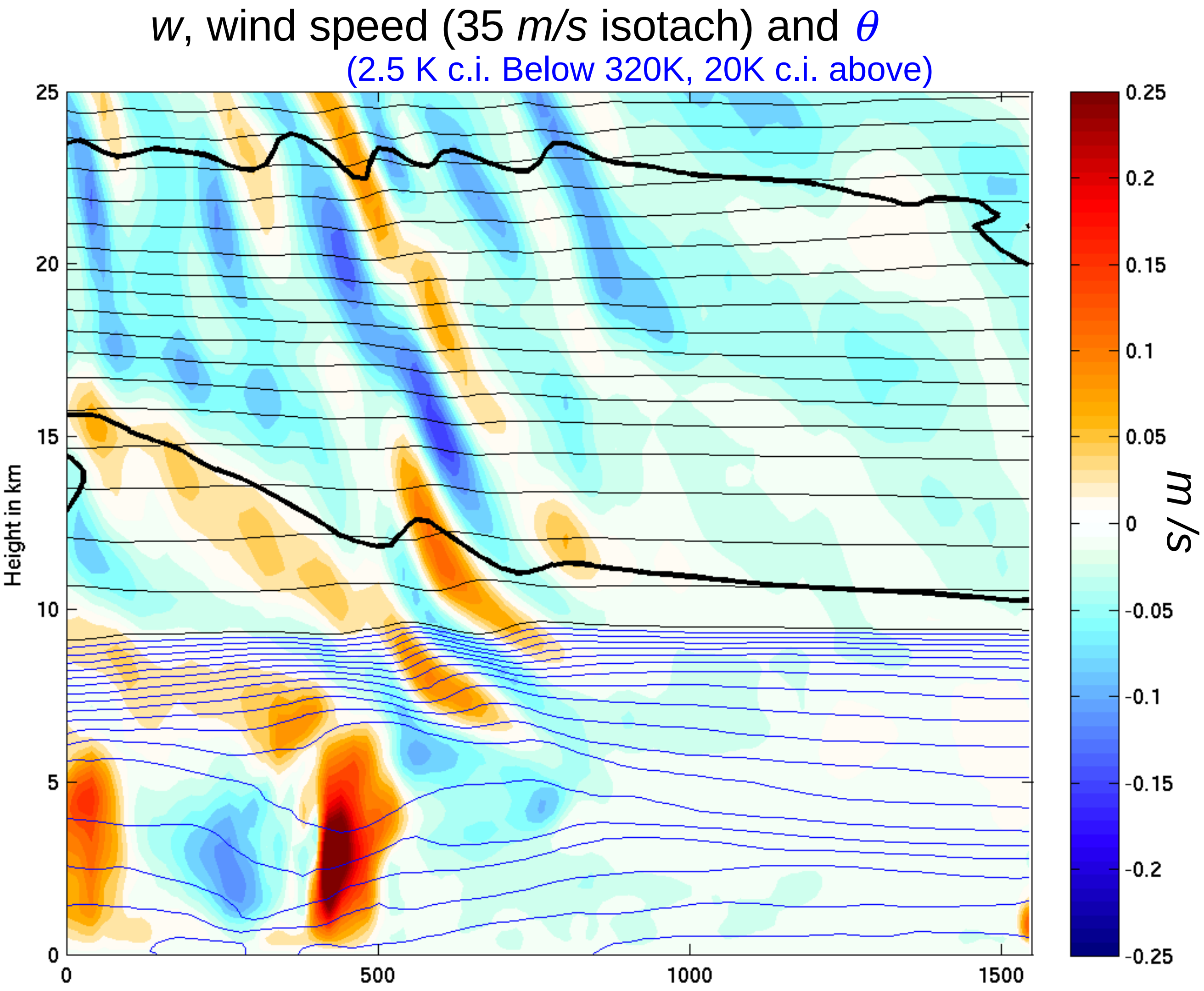


Vertical cross-section

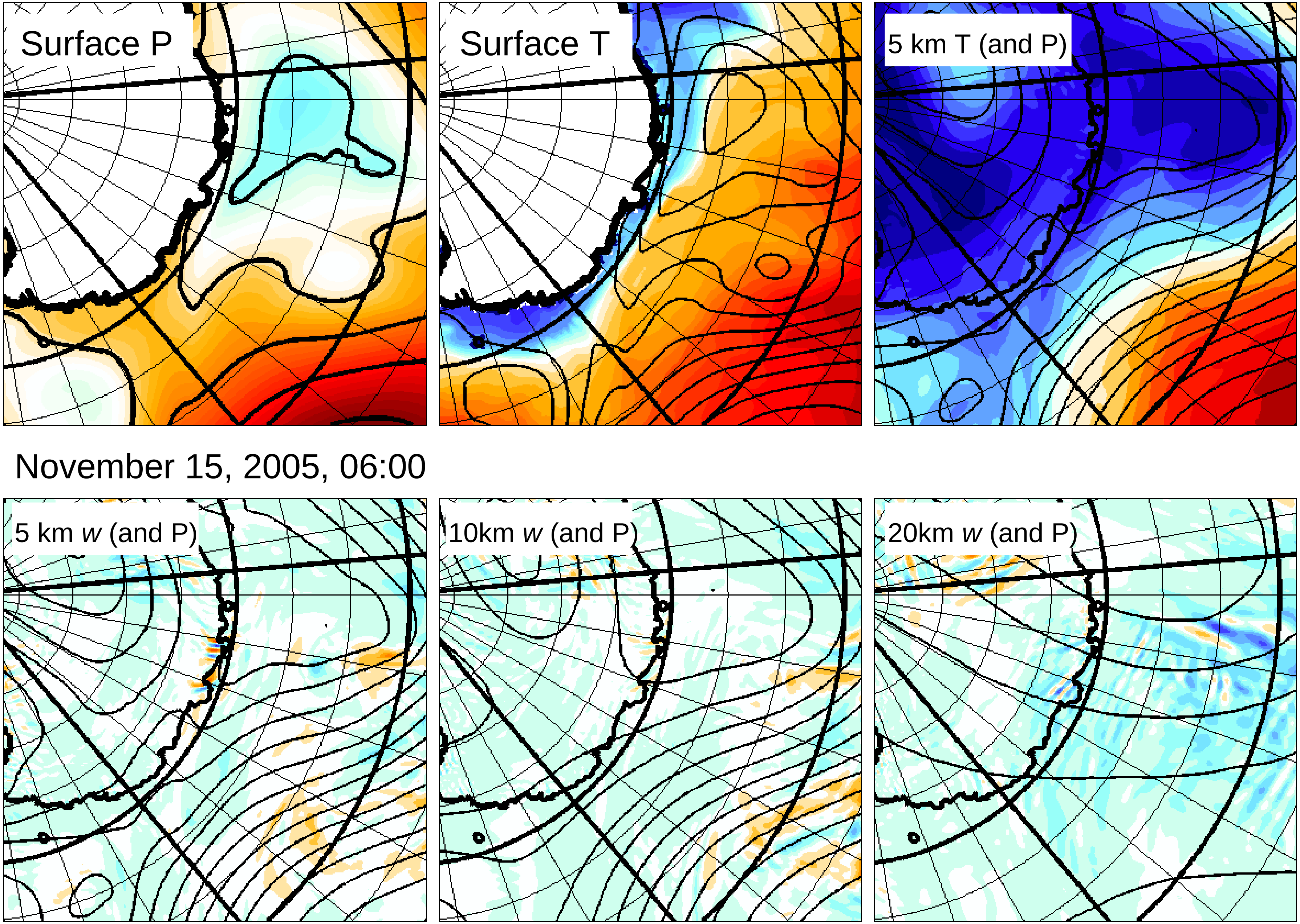


November 15, 2005, 06:00

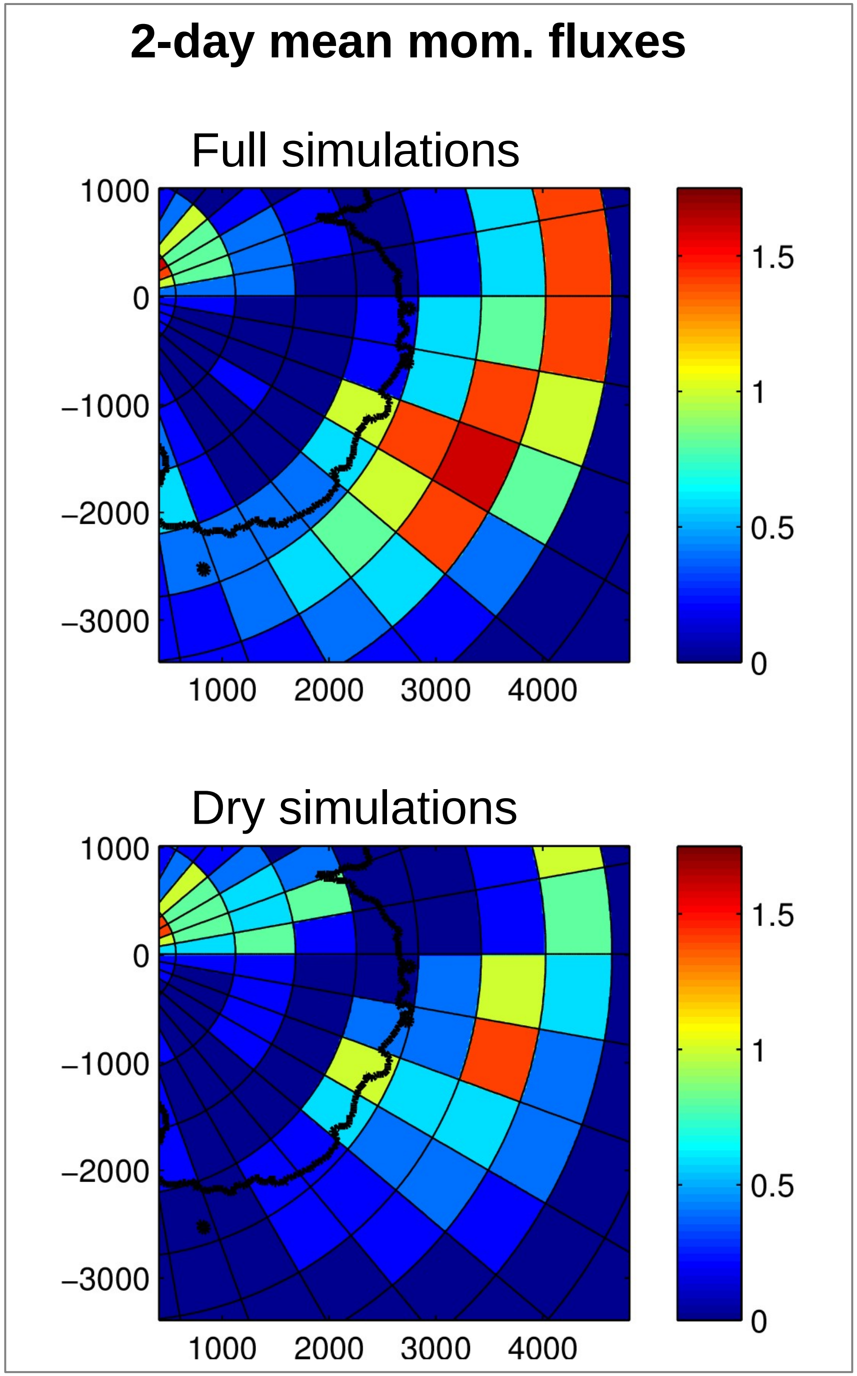




Dry run for comparison



Comparison of dry vs moist simulations



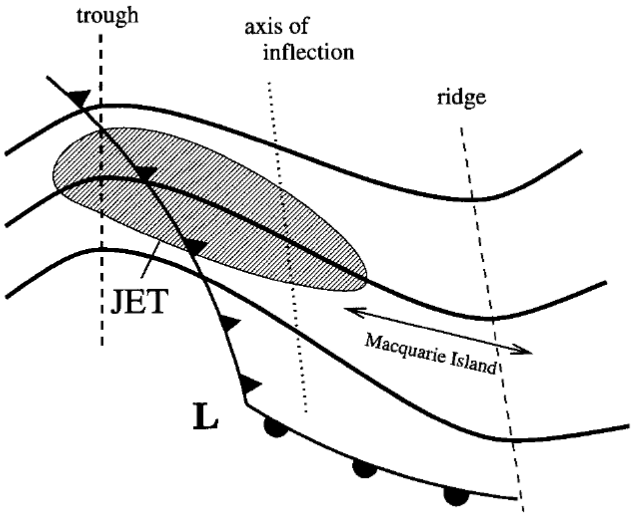
Momentum fluxes in the dry simulations are about **2.5 times weaker**

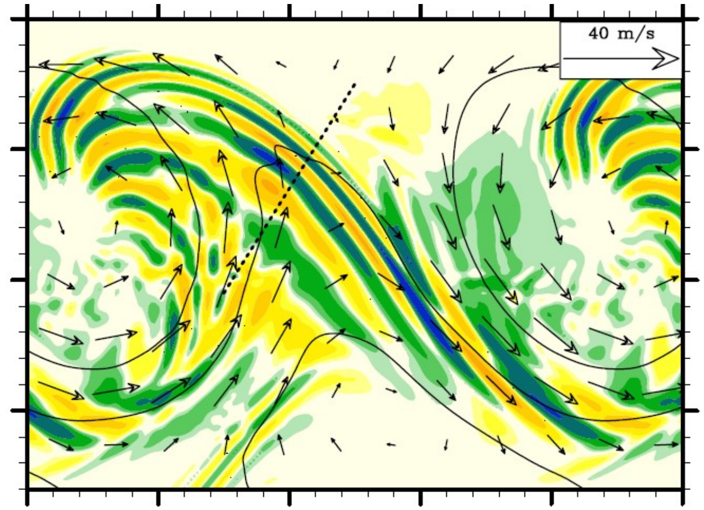
2

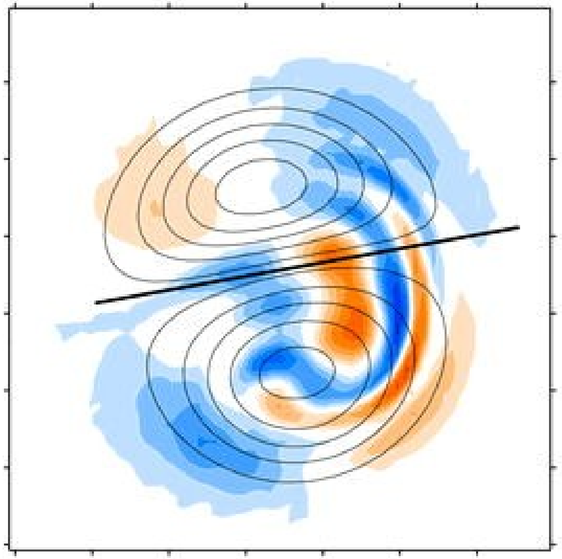
Moist convection near fronts appears to play a key rôle in exciting waves that are :

- **more intense**,
- **higher frequency** (5-10 *f* rather than 1.4 *f*)

than expected from dry idealized simulations.







Gravity waves generated from jets and fronts

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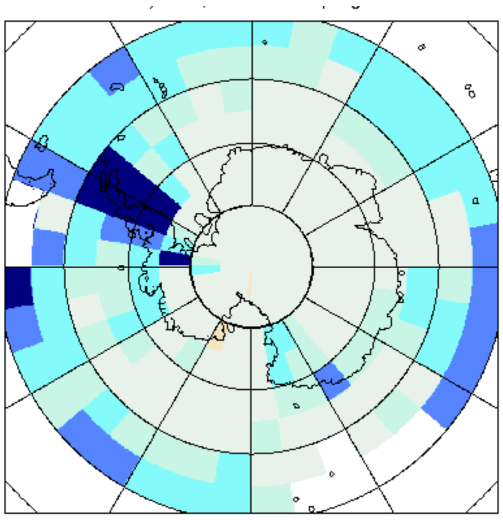

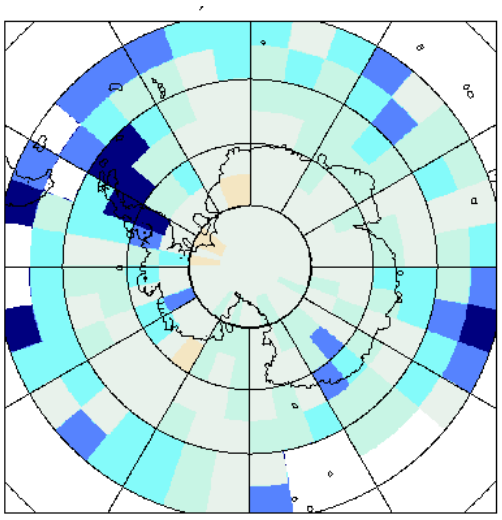

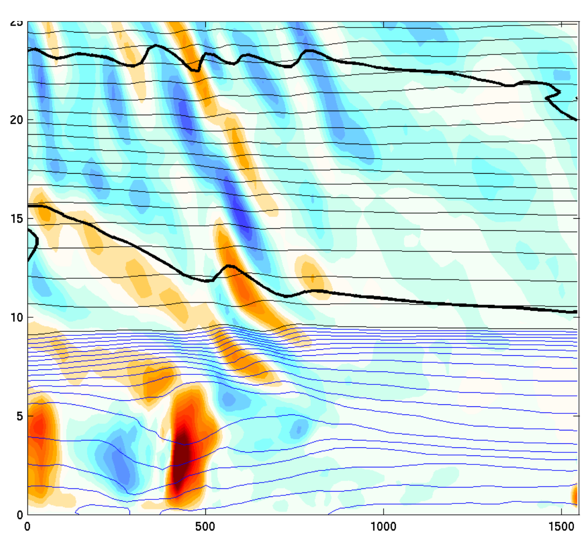

Conclusions and Discussion

Generation near jet exit region well understood :
Combined roles of generation and propagation, **wave-capture**.

Realism of simulated GW field in mesoscale simulations
→ potential use of analyses from operational centers ?

Non-orographic GW from jets and fronts
→ **significant contribution to momentum fluxes** into the stratosphere

Case studies emphasize the **rôle of moist processes**,
→ generating **more intense, higher frequency waves**

Remark : criteria used to identify the waves studied :

- observations : identifiable signal, e.g. in radiosonde profiles of wind
- idealized simulations : conspicuous signal emerging in the horizontal divergence
- real case simulations : gravity wave momentum fluxes at z = 20 km

Different criteria emphasize different elements of the gravity wave field ;
jet exit region waves are also present in the real case simulations

Conclusions and Discussion

For jet exit region waves **: backreaction of the waves on the flow**
backreaction in the case of the dipole for example ?

Other mechanisms present near jets and fronts:
- generation from fronts
- small-scale shear instabilities
- rôle of **vertical shear**

Can we find a **simple relation tying GW characteristics to the large-scale flow** ?
- wave-capture : local information...
- linearized equations on background flow : costly...

Intermittency, and pathways for parameterizations :
- **stochastic parameterization** (*Lott et al 2012*)
- in phase with **description of the GW using PDFs** (*Hertzog et al 2012*)

What **elements of GW parameterizations are crucial to validate ?**
which simplifying assumptions are most urgent to overcome (sources, column) ?

Thank you for your attention

A. Hertzog, M.J. Alexander and R. Plougonven (**2012**) On the intermittency of gravity wave momentum flux in the stratosphere, *J. Atmos. Sci. 69 (11), p3433-3448.*

R. Plougonven, A. Hertzog & L. Guez. (**2013**) Simulations of gravity waves above Antartica and the Southern Ocean and comparisons to balloon observations. Quart. J. Roy. Meteor. Soc., DOI:10.1002/qj.1965.

R. Plougonven & F. Zhang (**2014**). Internal gravity waves from atmospheric jets and fronts Rev. Geophys, 52, doi:10.1002/2012RG000419.

R. Plougonven, A. Hertzog and M.J. Alexander. (**2015**) Case studies of nonorographic gravity waves over the 1 Southern Ocean emphasize the role of moisture, J. Geophys. Res. Atmos., 120, doi:10.1002/2014JD022332.