The SPARC Gravity Wave Initiatives: A Historical Perspective

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Introduction

1. A historical survey of the use of radiosondes to study gravity waves with application to SPARC gravity wave initiatives
2. Focus on two SPARC initiatives: 1990-2005
3. What do radiosondes measure? Limitations and potential for bias
4. Some new ways to study GW using radiosondes

High Resolution Radiosonde Observations: I

Gravity wave activity in the lower atmosphere: Seasonal and latitudinal variations

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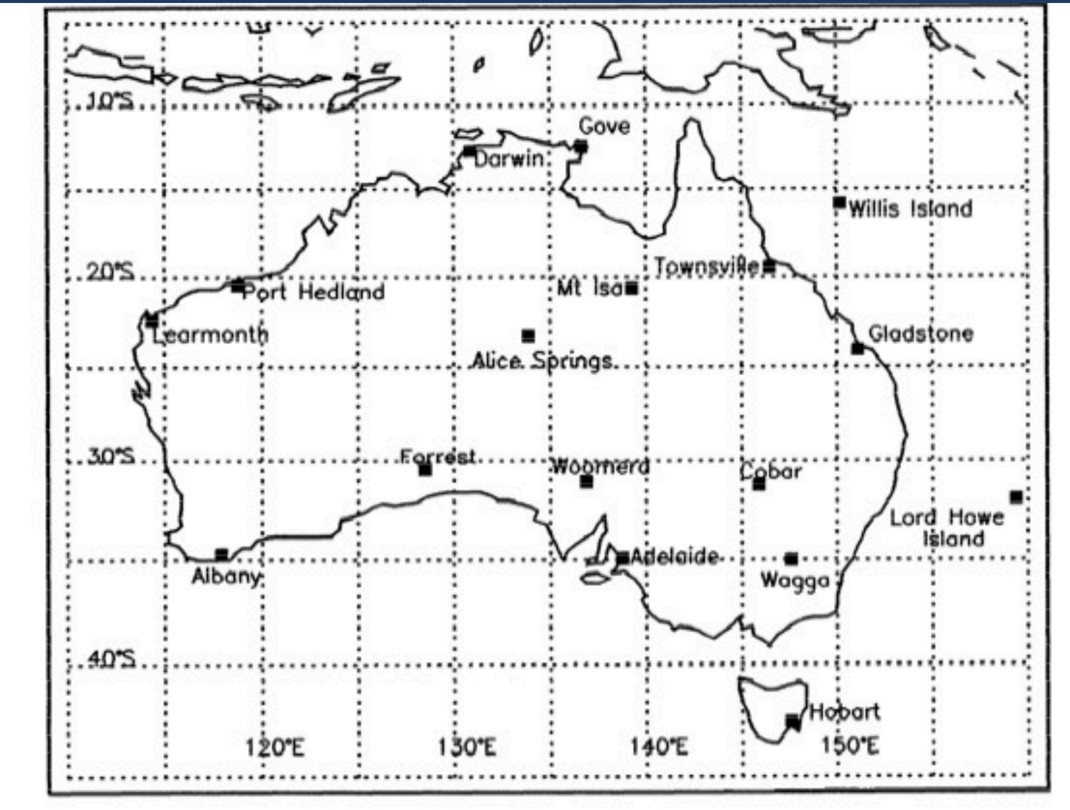
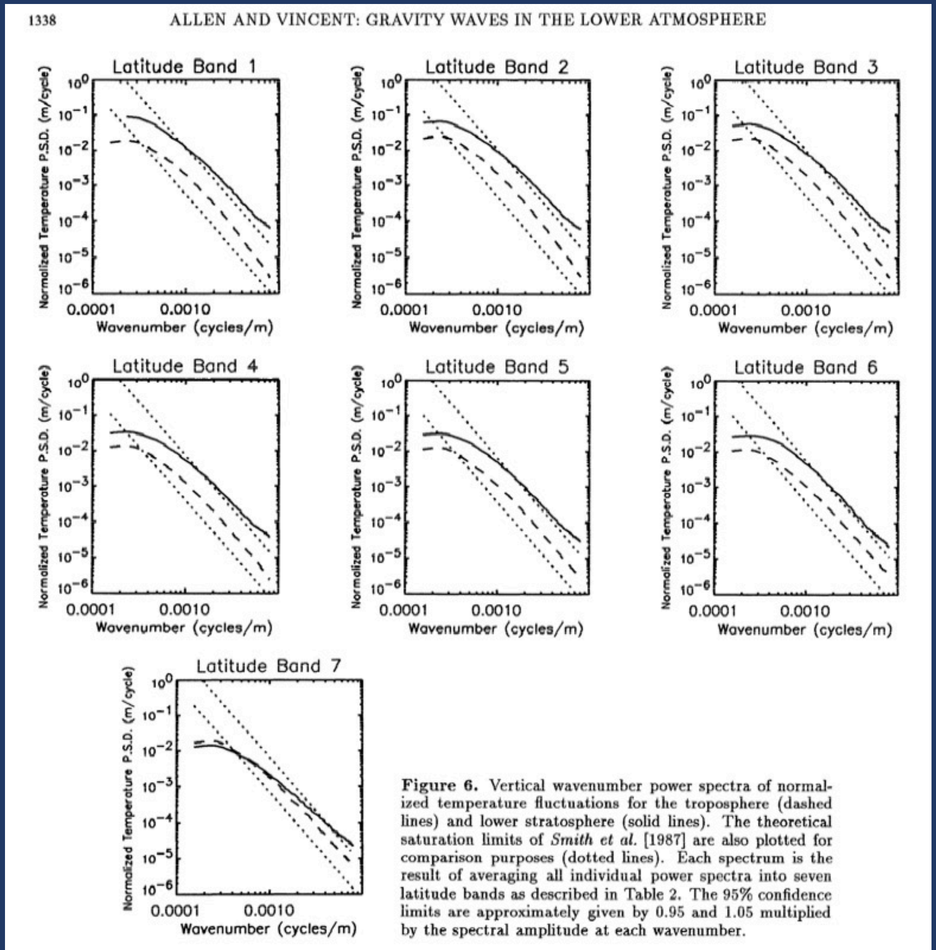
Abstract. A climatology of gravity wave activity in the lower atmosphere based on high-resolution radiosonde measurements provided by the Australian Bureau of Meteorology is presented. These data are ideal for investigating gravity wave activity and its variation with position and time. Observations from 18 meteorological stations within Australia and Antarctica, covering a latitude range of 12°S – 68°S and a longitude range of 78°E – 159°E, are discussed. Vertical wavenumber power spectra of normalized temperature fluctuations are calculated within both the troposphere and the lower stratosphere and are compared with the predictions of current gravity wave saturation theories. Estimates of important model parameters such as the total gravity wave energy per unit mass are also presented. The vertical wavenumber power spectra are found to remain approximately invariant with time and geographic location with only one significant exception. Spectral amplitudes observed within the lower stratosphere are found to be consistent with theoretical expectations but the amplitudes observed within the troposphere are consistently larger than expected, often by as much as a factor of about 3. Seasonal variations of stratospheric wave energy per unit mass are identified with maxima occurring during the low-latitude wet season and during the midlatitude winter. These variations do not exceed a factor of about 2. Similar variations are not found in the troposphere where temperature fluctuations are likely to be contaminated by convection and inversions. The largest values of wave energy density are typically found near the tropopause.



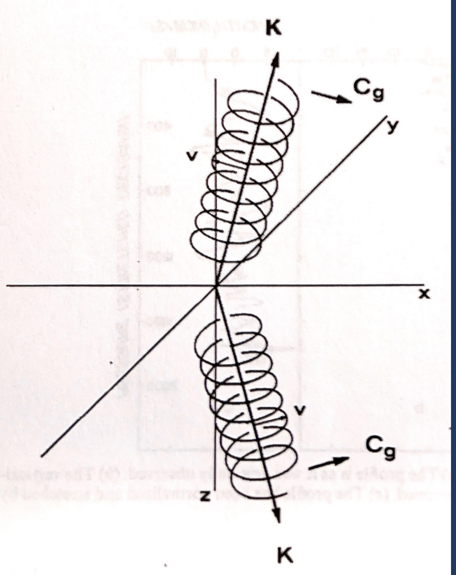
- From 1991 the Australian Bureau of Meteorology started to record and archive data at 10-sec (~50 m) intervals
- Limitation: temperature-only for most stations
- Radar and VLF DigiCora wind tracking available from some stations

High Resolution Radiosonde Observations: II

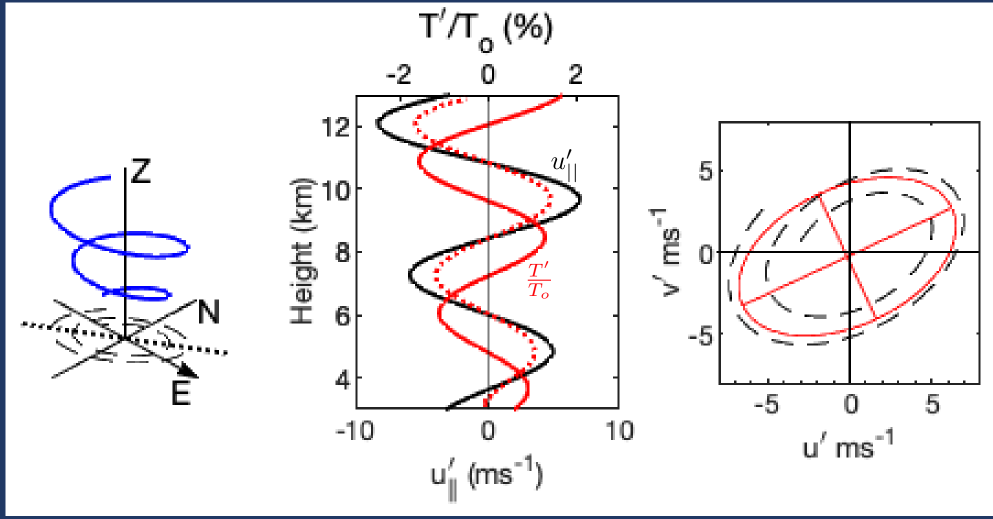


- Temperature spectra compared with theoretical spectra.
- General m^{-3} spectral slopes at high wavenumbers

Use of Wind Data I:
'Borrowing from the Oceanographers'



- Leaman and Sanford (Vertical energy propagation of inertial waves, JGR, 1975):
- Sense of rotation of wave motions with increasing depth gives direction of group (energy) propagation.



- Near inertial motions are elliptical
- Sense of rotation with height gives direction of propagation in the vertical
- Axial ratio gives $\hat{\omega}/f$
- 180° directional ambiguity in horizontal resolved using temperature profile

Use of Wind Data II

Quart. J. R. Met. Soc. (1978), **104**, pp. 691–698

551.510.532: 551.511.3

Observation of inertial waves in the stratosphere

By R. O. R. Y. THOMPSON

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(Received 19 October 1977; revised 10 January 1978)

SUMMARY

A series of radiosonde flights over Laverton, Victoria (38°S), is found to have sufficient vertical (100 m) and temporal (3 h) resolution, and sufficient length (28 days) to detect inertial waves. Fourier analysis shows that in the stratosphere there is a strong anticyclonic rotation of the wind vector which has energy concentrated near the local inertial frequency. This rotation is associated with a vertical wavelength between 1 and 3 km, and a downward phase propagation. There is no sign of inertial waves in the troposphere. The waves appear to be generated below the stratosphere and spread upwards.

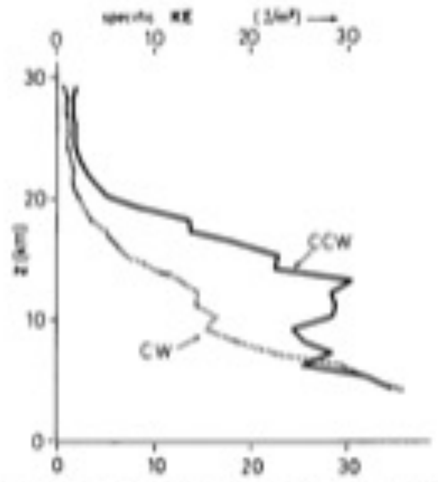


Figure 2. Kinetic energy per unit volume at wavenumber 4 (wavelength 1·6 km) versus central height of the 6·4 km block, computed from all the 221 soundings, except for blocks with missing data. CW: clockwise rotation; CCW: counterclockwise.

- Application to standard radiosonde observations taken near Melbourne by Thompson (1978)
- Counter-clockwise (CCW) motions dominate with increasing height
- Denotes upward energy propagation in the SH

Use of Wind Data III: Stokes Parameters

- Other developments:
  - Application to rocketsonde observations in stratosphere (Hirota and Niki, JMSJ, 1985)
  - Use of Stokes Parameters technique to statistically quantify wave field (Vincent and Fritts, JGR, 1987)
  - Eckermann (1995) provides relationship of Stokes Parameters to other spectral techniques

$$u'(z) \leftrightarrow U_R(m) + iU_I(m)$$

$$\begin{aligned}
I &= \overline{u'^2} + \overline{v'^2} = \left(\overline{U_R^2(m)} + \overline{U_I^2(m)}\right) + \left(\overline{V_R^2(m)} + \overline{V_I^2(m)}\right) \\
D &= \overline{u'^2} - \overline{v'^2} = \left(\overline{U_R^2(m)} + \overline{U_I^2(m)}\right) - \left(\overline{V_R^2(m)} + \overline{V_I^2(m)}\right) \\
P &= 2\overline{u'v'\cos\delta} = 2\left(\overline{U_R(m)V_R(m)} + \overline{U_I(m)V_I(m)}\right) \\
Q &= 2\overline{u'v'\sin\delta} = 2\left(\overline{U_R(m)V_I(m)} - \overline{U_I(m)V_R(m)}\right)
\end{aligned}$$

Hamilton and Vincent (EOS, 1995)

Eos, Vol. 76, No. 49, December 5, 1995

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS

VOLUME 75 NUMBER 49

DECEMBER 5, 1995

PAGES 609–616

High-Resolution Radiosonde Data Offer New Prospects for Research

PAGES 497, 506–407

Kevin Hamilton and Robert A. Vincent

Determination of Gravity Wave Characteristics

High-resolution radiosonde observations can be exploited to study gravity waves. *Allen and Vincent* [1995] used high-resolution radiosonde temperature data from 18 stations in the ABM network to investigate gravity wave activity in the troposphere and lower stratosphere. They considered the effects of sensor lag on the temperature soundings and concluded that the effective vertical resolu-

- Position paper that outlined advantages of using high-resolution radiosonde data to study gravity waves
- Urged other meteorological agencies to archive high-resolution data
- Led to the start of the SPARC project on use of radiosonde data to study GW
- Temperature-only data gives incomplete picture of GW activity

SPARC GW Initiatives

Radiosonde Project

- April 1996, Santa Fe: GW meeting
- Dec 1996, Adelaide: SPARC SSG
- May 1997, Victoria BC: GW workshop
- Nov 1997, Pt Jefferson: SPARC SSG
- June 1998, Boulder: Planning meeting
- July 1999, Abingdon: Two-day workshop

CEGWE

- May 1995: Proposal for ***C***onvective ***E***xcitation of ***GW E***xperiment, ALOHA workshop, Lanai
- April 1996, Santa Fe: Proposed to SPARC SSG
- Dec 1996: Further discussions, Melbourne/Adelaide
- Dec 1997: Full endorsement by SPARC SSG

Radiosonde Initiative Workshop 15-16 July 1999
Cosner's House, Abingdon, UK

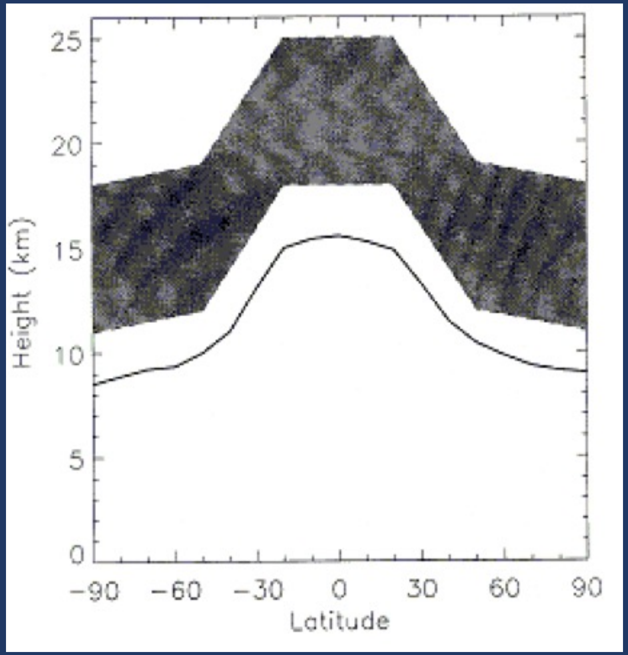
Participants

Joan Alexander (USA)
Mark Baldwin (USA)
HyeYeong Chun (Korea)
Andreas Doernbrak (Germany)
Tom Duck (Canada)
Marvin Geller (USA)
Lesley Gray (U. K.)
Christian Haeberli (Austria)
Kevin Hamilton (USA)
David Karoly (Australia)
Tobias Kerzenmacher (U. K.)

Rigel Kivi (Finland)
Bryan Lawrence (New Zealand)
Stephen Mobbs (U. K.)
Kaoru Sato (Japan)
Atsushi Shimizu (Japan)
Kathrin Shulz-Scullhammer (Germany)
Werner Singer (Germany)
Bob Vincent (Australia)
Jim Whiteway (U.K.)
Y. Yoshiki (Japan)

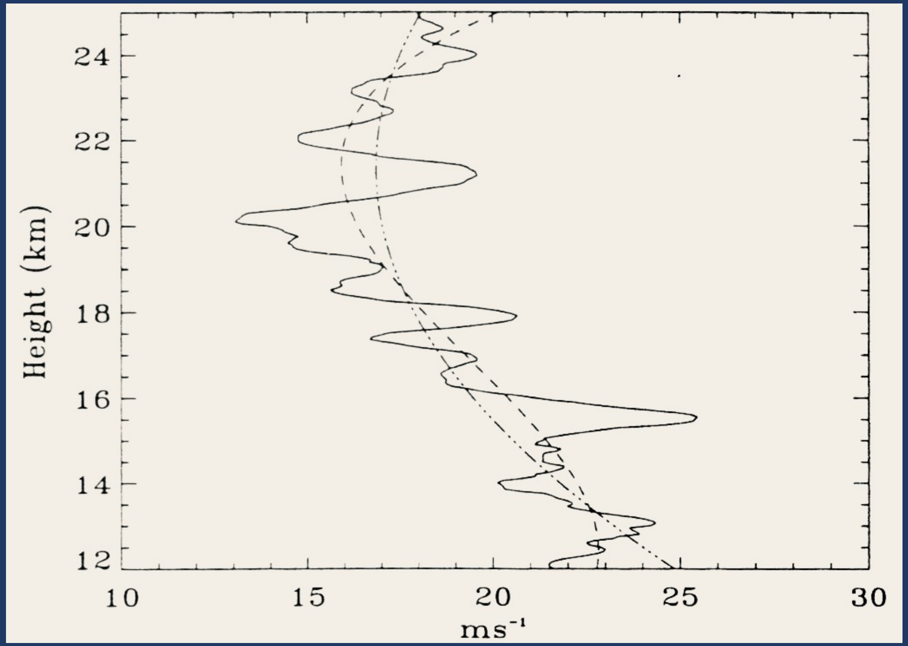
Radiosonde Initiative Workshop 15-16 July 1999
Topics: I

Height Coverage



- Height coverage 7-km in lower stratosphere mean level ~100 hPa
- Tropopause analysis: Hoinka (MWR, 1998)

Background Removal



- 2nd order polynomial to remove background wind and temperature

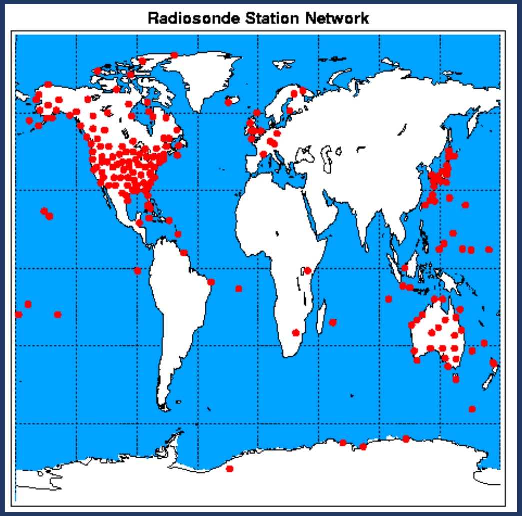
Radiosonde-Initiative Workshop 15-16 July 1999: Topics and Products

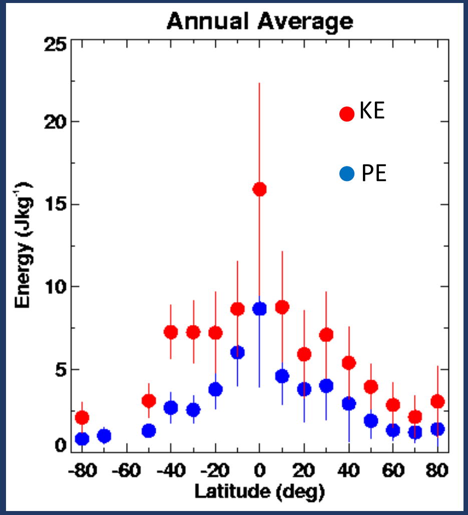
- Quality control
- Height averaging intervals
- Spatial and temporal intermittency
- Problems with dealing with different wind measuring techniques
  - Radar tracking (RDF)
  - OMEGA navigation system

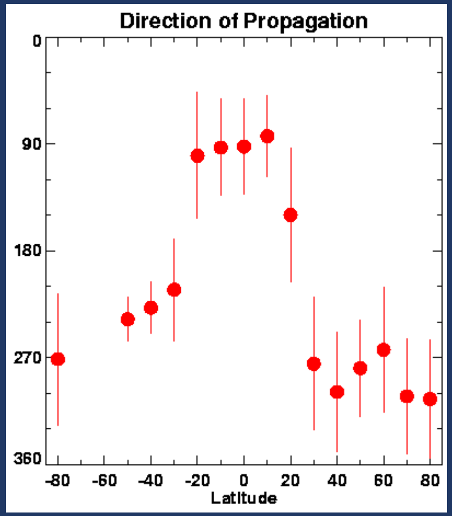
- GW horizontal wavelengths
- Phase velocities
- Momentum fluxes (?)
- Vertical velocity wind perturbations derived from variability is ascent rates
- Suite of IDL programs for common data analysis

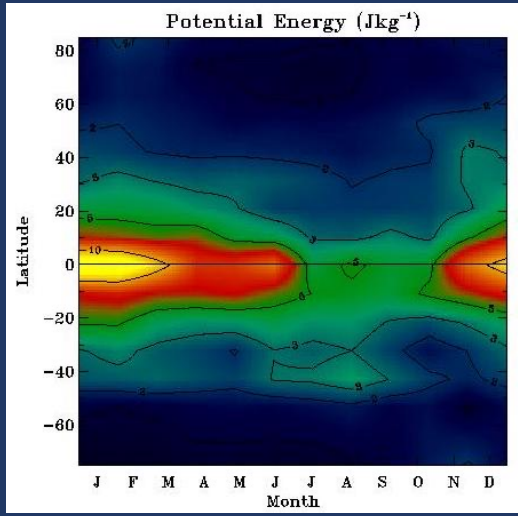
"Participants are encouraged to produce these products, although it is realised that the results are based on assumptions that may not be valid and are still the subject of research."

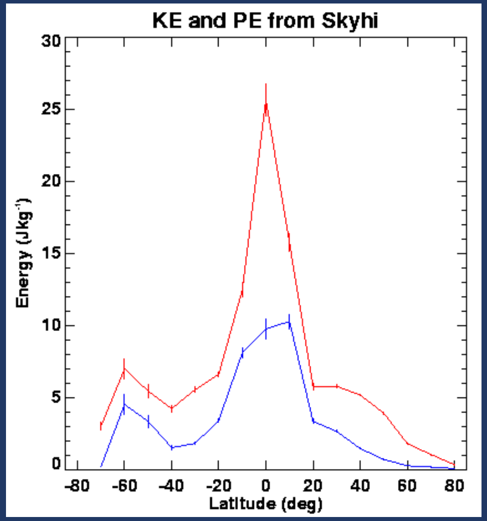
Radiosonde-Initiative : Some Stratospheric Results

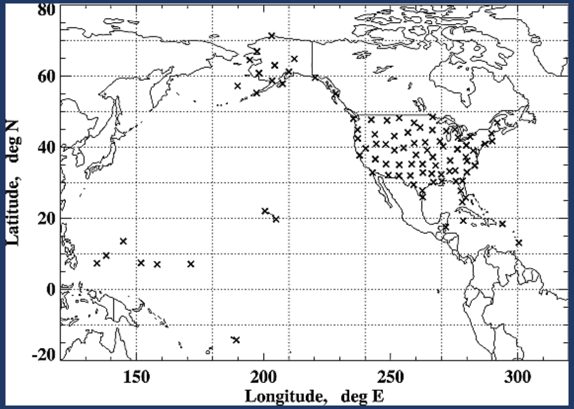


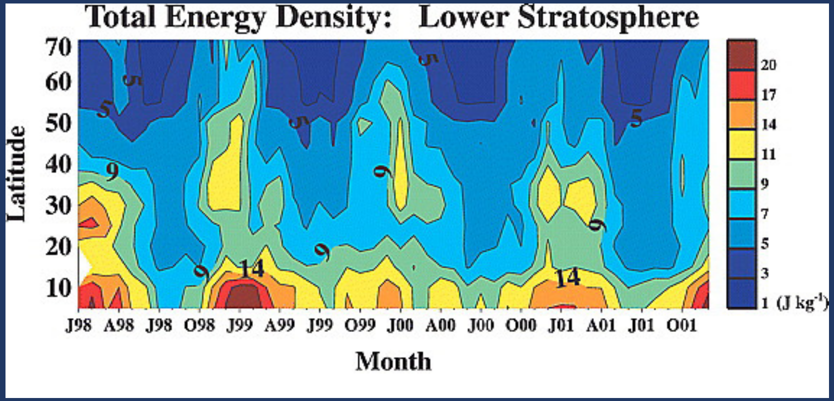












Examples of outcomes: Wang and Geller (2003)

CEGWE/Darwin Area Experiment (DAWEX)

- Focus on HECTOR events
    - Strong convective events forced by island sea breeze convergence
- Three campaigns: October, November and December 2001 during build up to monsoon
- Multiple instruments in Darwin area and across Australia
- Results published in JGR Special Section 2004 (seven papers)

DAWEX overview:

(H04) Hamilton, Vincent and May, *Darwin Area Wave Experiment (DAWEX) field campaign to study gravity wave generation and propagation*, JGR, 109, 2004

Radiosonde observations:

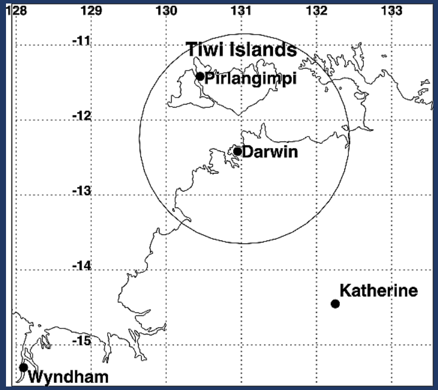
(T04) Tsuda et al: *Characteristics of gravity waves with short vertical wavelengths observed with radiosonde and GPS occultation during DAWEX (Darwin Area Wave Experiment),* JGR, 109, 2004

GW Generation:

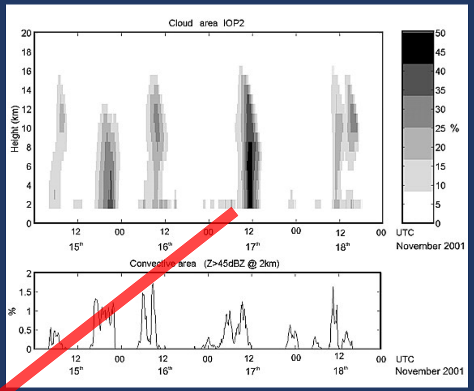
(A04) Alexander et al., *Gravity waves generated by convection in the Darwin area during the Darwin Area Wave Experiment,* JGR, 109, 2004

Some DAWEX Outcomes

Radiosonde launch sites and C-Pol radar coverage (H04)



C-Pol reflectivities IOP 2 (H04)

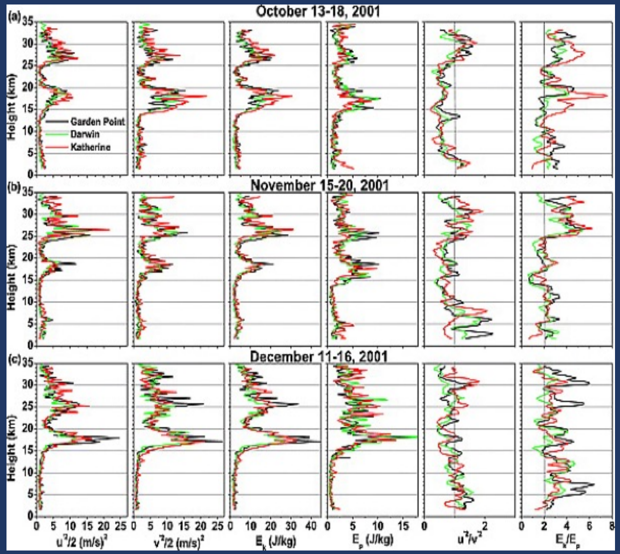


$\frac{1}{2}\overline{u'^2}$ $\frac{1}{2}\overline{v'^2}$ E_k E_p $\frac{\overline{u'^2}}{\overline{v'^2}}$ E_k/E_p

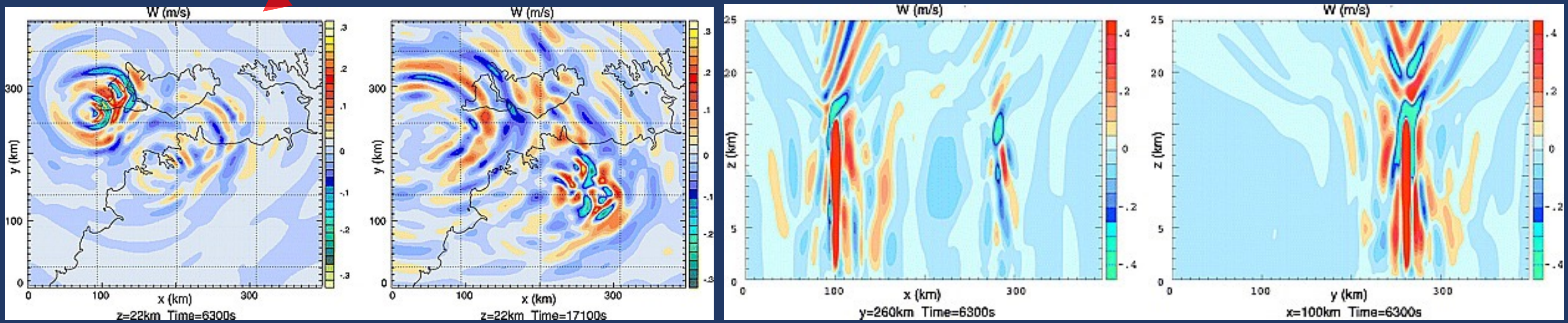
$IOP1$

$IOP2$

$IOP3$



Height variations of energy (T04)

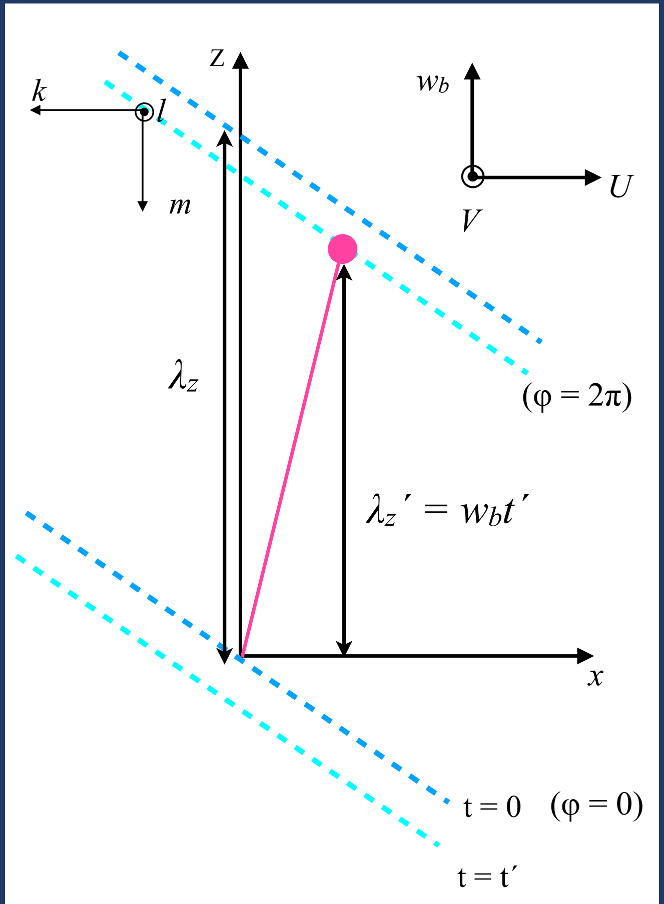


Model GW instantaneous *w'* 17/11/2004 (A04)

What do Radiosondes Actually Measure? Biases in GW Vertical Wavelength: I

- How accurate are GW vertical wavelengths derived from radiosonde observations?
- Sondes ascend with a speed $w_b \sim 5\,\mathrm{ms}^{-1}$
- Wave fronts move (descend) with vertical phase speed, $\hat{c}_z$
- In general, there is a horizontal wind (U, V)
- Measured vertical wavelength, λ'_z, different to actual wavelength, λ_z
- Problem considered by:
  - Gardner and Gardner (JGR, 1993)
  - de la Torre and Alexander (JAMC, 1996)
  - Guest et al. (JAS, 2000)

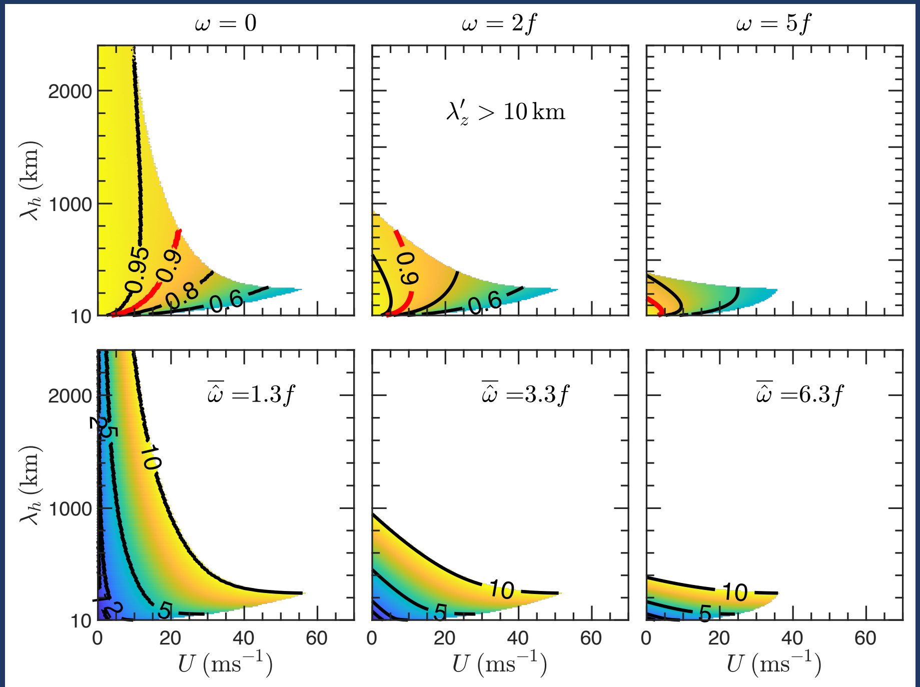
What do Radiosondes Actually Measure? Biases in GW Vertical Wavelength: II



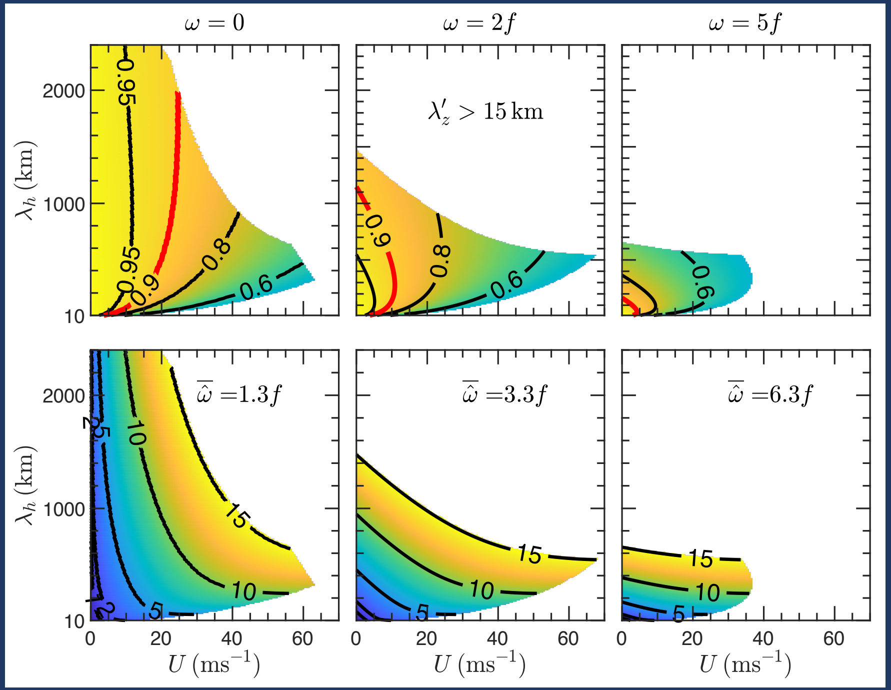
- Assume uniform horizontal wind $(U(x), V(y))$
- In an **intrinsic reference frame**, the apparent vertical wavelength is $\lambda_z' = w_b t'$
- $\lambda_z' = \left(\frac{w_b}{w_b + |\hat{c}_z|}\right) \lambda_z$
- For $\lambda_z' \approx \lambda_z$ require $\frac{\hat{c}_z}{w_b} \ll 1$ (Guest et al., 2000)
- i.e. need $\frac{\hat{c}_z}{w_b} < 0.1$

What do Radiosondes Actually Measure?
Biases in GW Vertical Wavelength III

10 km observational window



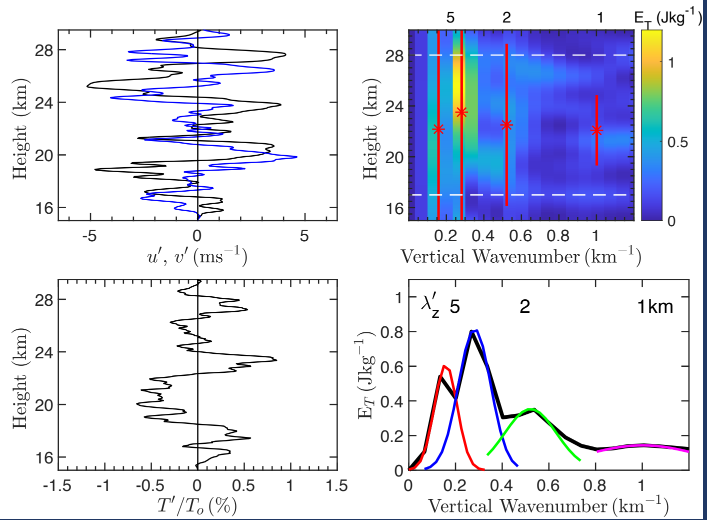
15 km observational window



$$\boxed{U_{crit} \sim 20\,\mathrm{ms}^{-1}}$$

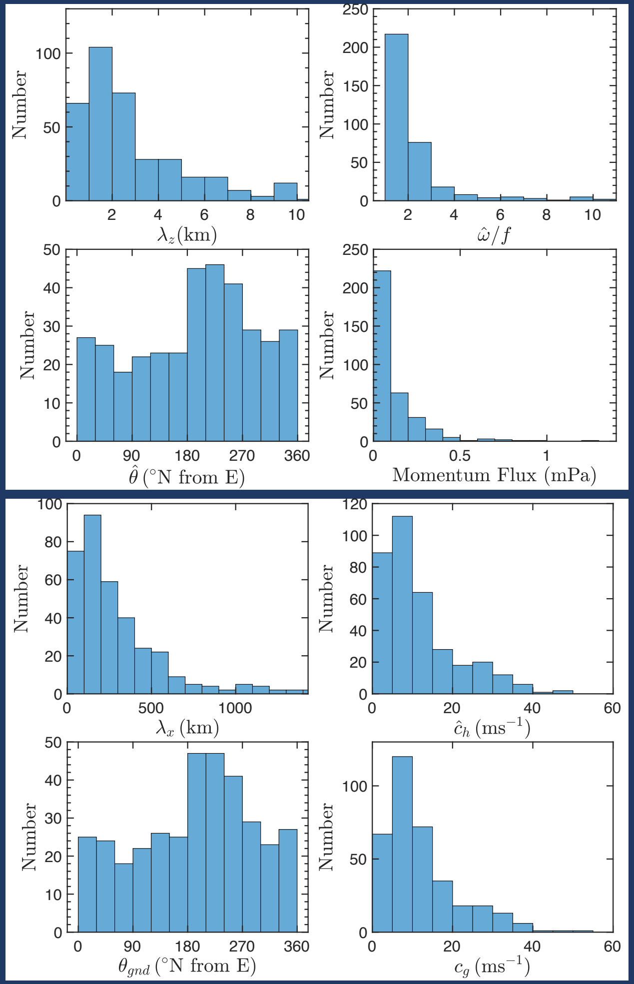
Another Way to Analyse Sonde Observations?

Use *S*-transforms to decompose wind and temperature height profiles



Parameters	Mode 1	Mode 2	Mode 3	Mode 4
$\overline{u}'^2$ (m²s⁻²)	0.60	1.11	0.30	0.19
$\overline{v}'^2$ (m²s⁻²)	0.27	0.26	0.30	0.07
λ_z (km)	6.3	3.6	1.9	1.0
AxR	1.42	2.3	1.74	3.6
$\hat{\omega} \times 10^4$ (s⁻¹)	1.9	3.0	2.2	4.7
$\overline{u'w'} \times 10^3$ (m²s⁻²)	-2.8	4.6	0.8	2.8
$\overline{v'w'} \times 10^3$ (m²s⁻²)	0.5	-0.7	1.4	1.4
$\rho_o \lvert \overline{U'w'} \rvert$ (mPa)	0.25	0.34	0.13	0.28
θ (deg)	169	312	62	26
λ_h (km)	918	279	215	45

Sonde: 00 UT 1 June 2010
Fairbanks, Alaska



Data for June-July Fairbanks, Alaska
$\overline{u} = -5\,\mathrm{ms}^{-1}$
$\overline{v} = 0.5\,\mathrm{ms}^{-1}$

SPARC SSG Buenos Aires December 2000