Progress Report on DEEPWAVE Science Projects at NRL DC

Stephen D. Eckermann[1], Jun Ma[2], Dave Broutman2, David D. Kuhl[3], Karl W. Hoppel[3], John P. McCormack[1], James D. Doyle[4], Qingfang Jiang[4], P. Alex Reinecke[4], Carolyn Reynolds[4], Benjamin C. Ruston[4], Nancy L. Baker[4], Kevin C. Viner[4], Timothy R. Whitcomb[4], Timothy F. Hogan[4] *and* **Melinda S. Peng[4]**

1. Space Science Division, Naval Research Laboratory, Washington, DC
2. Computational Physics, Inc., Springfield, Virginia
3. Remote Sensing Division, Naval Research Laboratory, Washington, DC
4. Marine Meteorology Division, Naval Research Laboratory, Monterey, CA

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Progress Report on Following Topics

NAVGEM Reanalysis for 2014 DEEPWAVE Austral Winter *(Update)*

Stratospheric Gravity Waves in AIRS and CrIS 15µm and 4.3 µm Radiances *(New Results)*

Deep Gravity-Wave Dynamics over the Auckland Islands and Macquarie Island during RF23 *(Plug for AGU Talk)*

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Motivation for DEEPWAVE Reanalysis

- DEEPWAVE acquired gravity wave observations from 0-100 km altitude, with a concentration of MLT observations from ~80-95 km (AMTM, Na lidar, NZ airglow imagers)
- Modeling of these deep wave observations requires (*inter alia*) knowledge of the background environment for wave generation and propagation from 0-100 km
  - Backgrounds for linear ray models and parameterizations
  - Lateral boundary conditions for regional models (COAMPS®, WRF)
  - Diagnostics of wave propagation (critical levels, ducting, etc.)
- Such fields are provided by atmospheric reanalyses
- Existing centers (ECMWF, NASA GMAO, NOAA, FNMOC, Met Office, NIWA) issue reanalyses up to 65-80 km only.
- **There is a "reanalysis gap" from ~70-100 km that limits modeling of DEEPWAVE gravity-wave observations in MLT**

NAVGEM Reanalysis Experiments for 2014 DEEPWAVE Austral Winter

Old Reanalysis Experiments (completed June 2016)

	Synoptic	GW Resolving
Pure 4DVAR:	**T119L74**	**T425L74**
Hybrid 4DVAR:	**T119L74**	**T425L74**
(Inner Loops)	T47L74	T119L74

Problems discovered and updates

- 0000 UTC MLS & SABER data assimilation bug (-24 h time offsets for data @0000 UTC)
- Used MLS version 2 retrievals (newer hires version 4 MLS data now fully backfilled)
- New v4 MLS background error covariances & v4 MLS/v2 SABER bias correction profiles
- MLS data missing from initial T119L74 Hybrid 4DVAR run (corrected)
- MLS & SABER data lost from HPC data repository during T425L74 4DVAR run
- MLS mesospheric water vapor not optimally assimilated (error reduction code not active)

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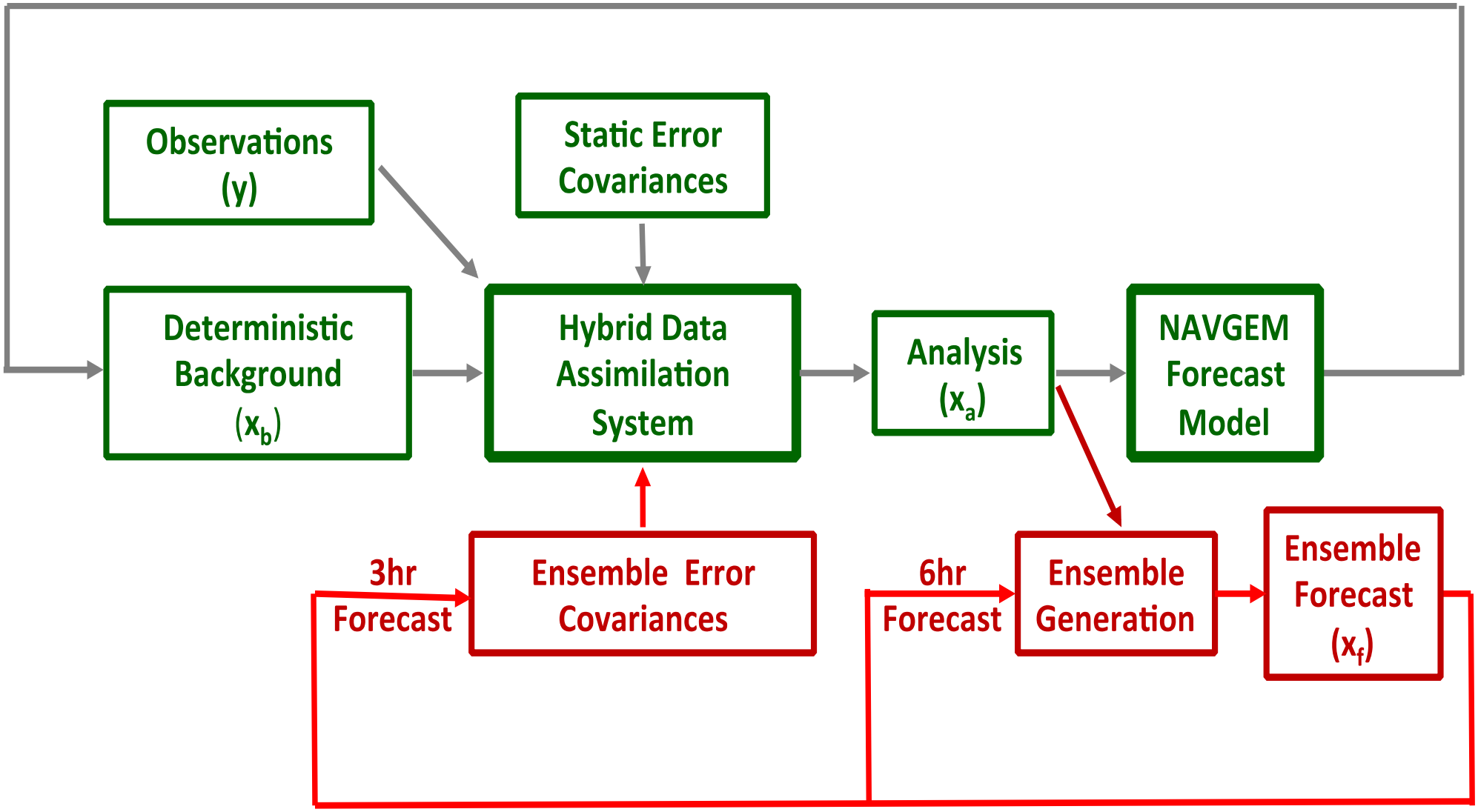
Different NAVGEM Analysis Configurations

Hybrid 4DVAR **Pure 4DVAR**



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NAVGEM Experiments

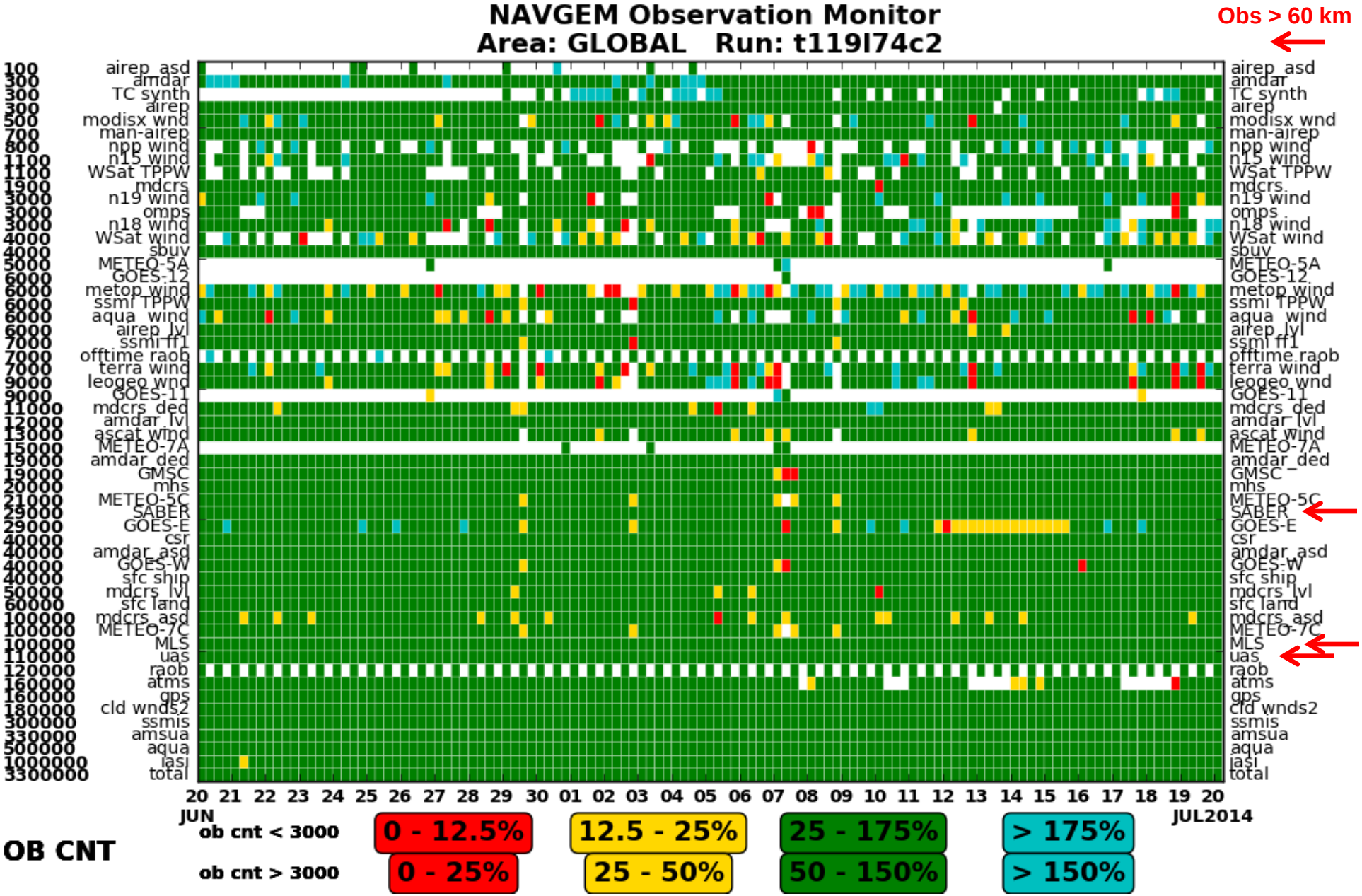
Old Reanalysis Experiments (completed June 2016)

	Synoptic	GW Resolving
Pure 4DVAR:	T119L74	T425L74
Hybrid 4DVAR:	T119L74	T425L74
(Inner Loops)	T47L74	T119L74

Status of Corrected/Updated Reanalysis Runs

	Synoptic	GW Resolving
Pure 4DVAR:	2 Oct 2014	16 June 2014
Hybrid 4DVAR:	28 Aug 2014	29 April 2014

>3M Observations Assimilated Per Cycle from 0-110 km Altitude



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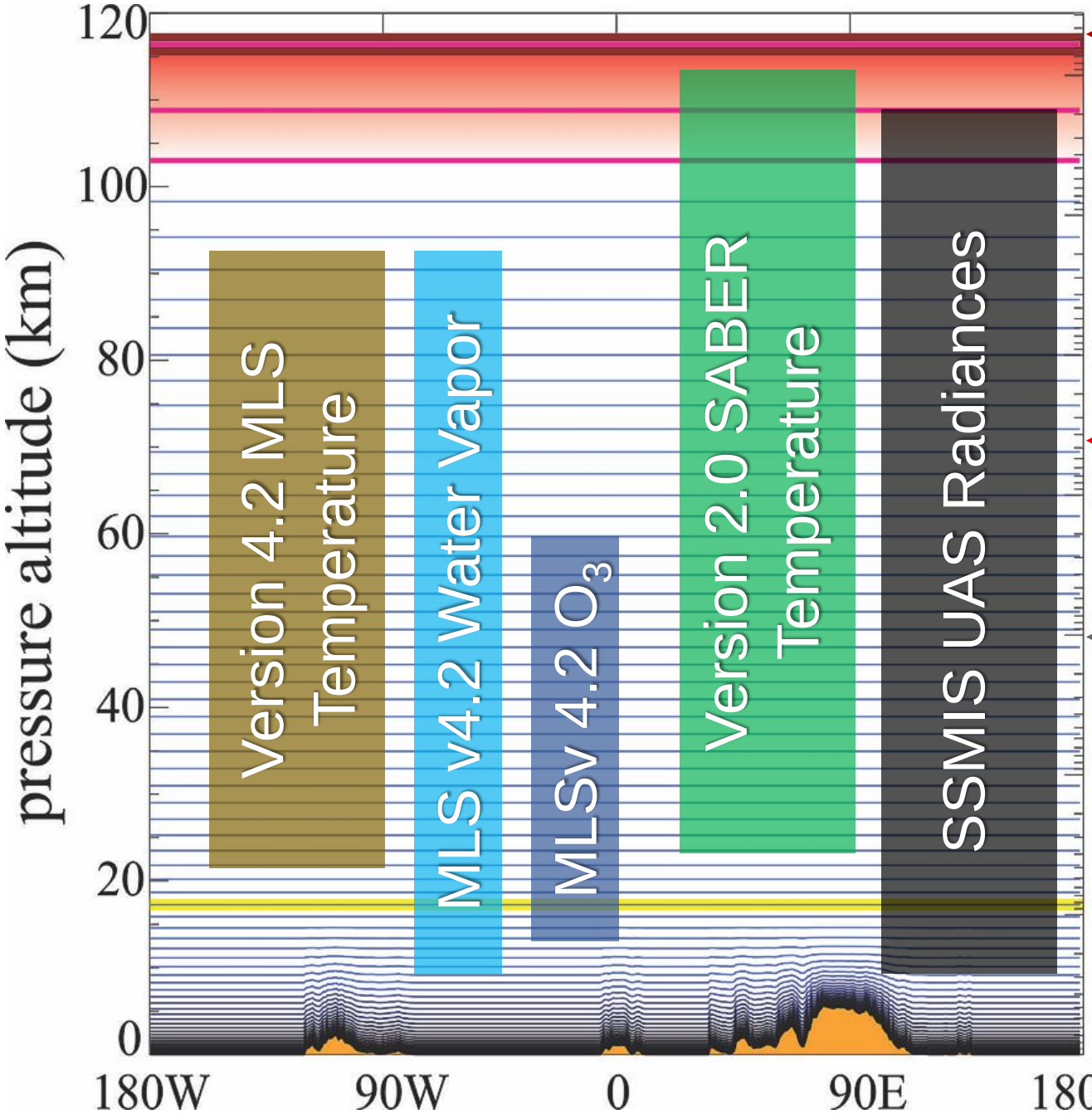
NAVGEM Reanalyses for DEEPWAVE Austral Winter (T119L74 & T425L74)



Reanalysis Upper Boundary
p_{top}=6x10^{-5} hPa

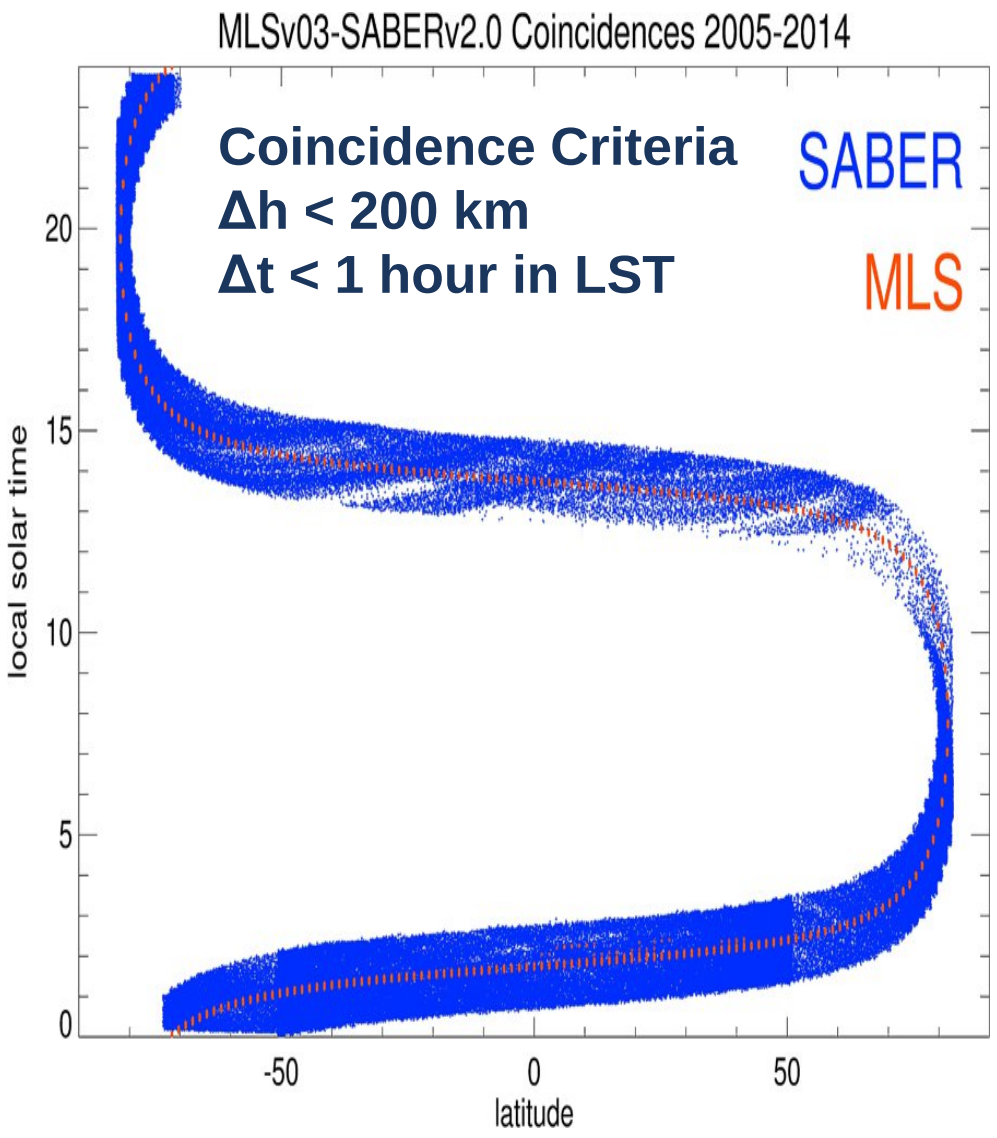
Both Pure 4DVAR & Hybrid Ensemble 4DVAR Reanalyses

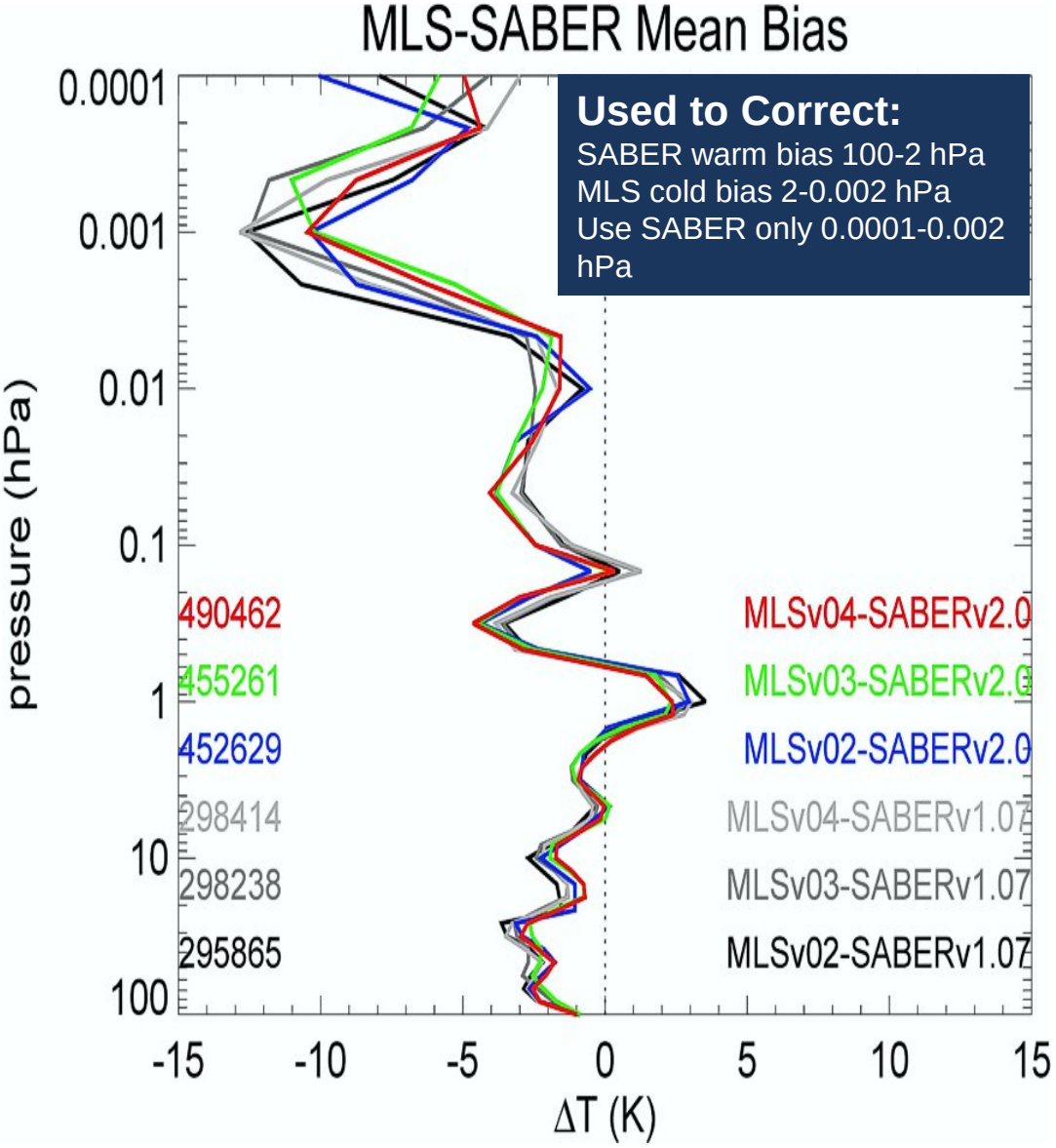
Current Operational Upper Boundary

Top Data Level Assimilated Operationally

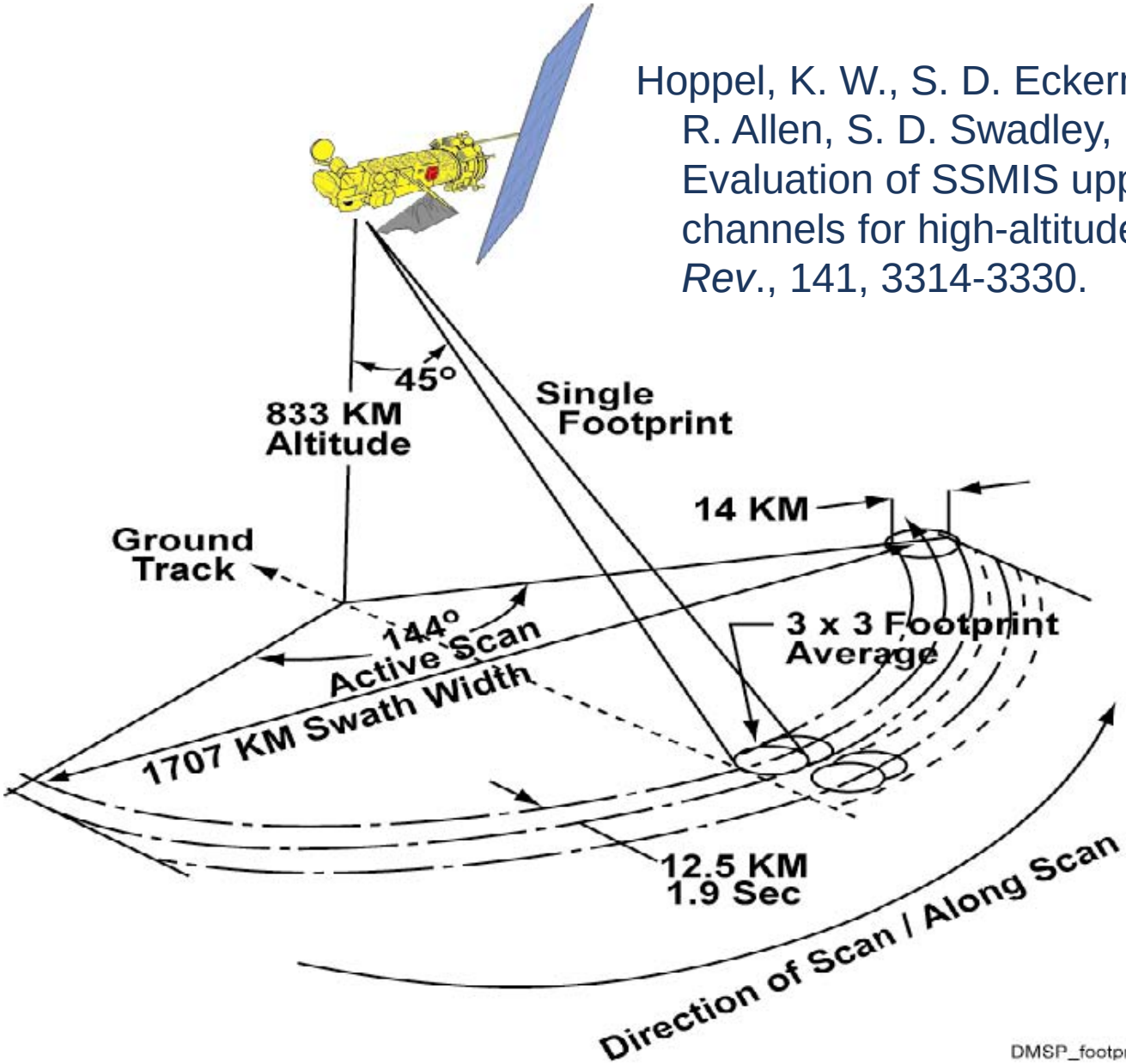
The NGV Dropwindsonde Data Assimilated via the GTS

SABER-MLS Biases from 11-Year Coincidences





Operational Assimilation of SSMIS UAS Radiances Using NAVGEM



Hoppel, K. W., S. D. Eckermann, L. Coy, G. E. Nedoluha, D. R. Allen, S. D. Swadley, and N. L. Baker (2013), Evaluation of SSMIS upper atmosphere sounding channels for high-altitude data assimilation, *Mon. Wea. Rev.*, 141, 3314-3330.

Special Sensor Microwave Imager/Sounder (SSMIS)

SSMIS is deployed on 4 operational Defense Meteorological Satellite (DMSP) platforms (F16-F19): F16 UAS was not available during DEEPWAVE

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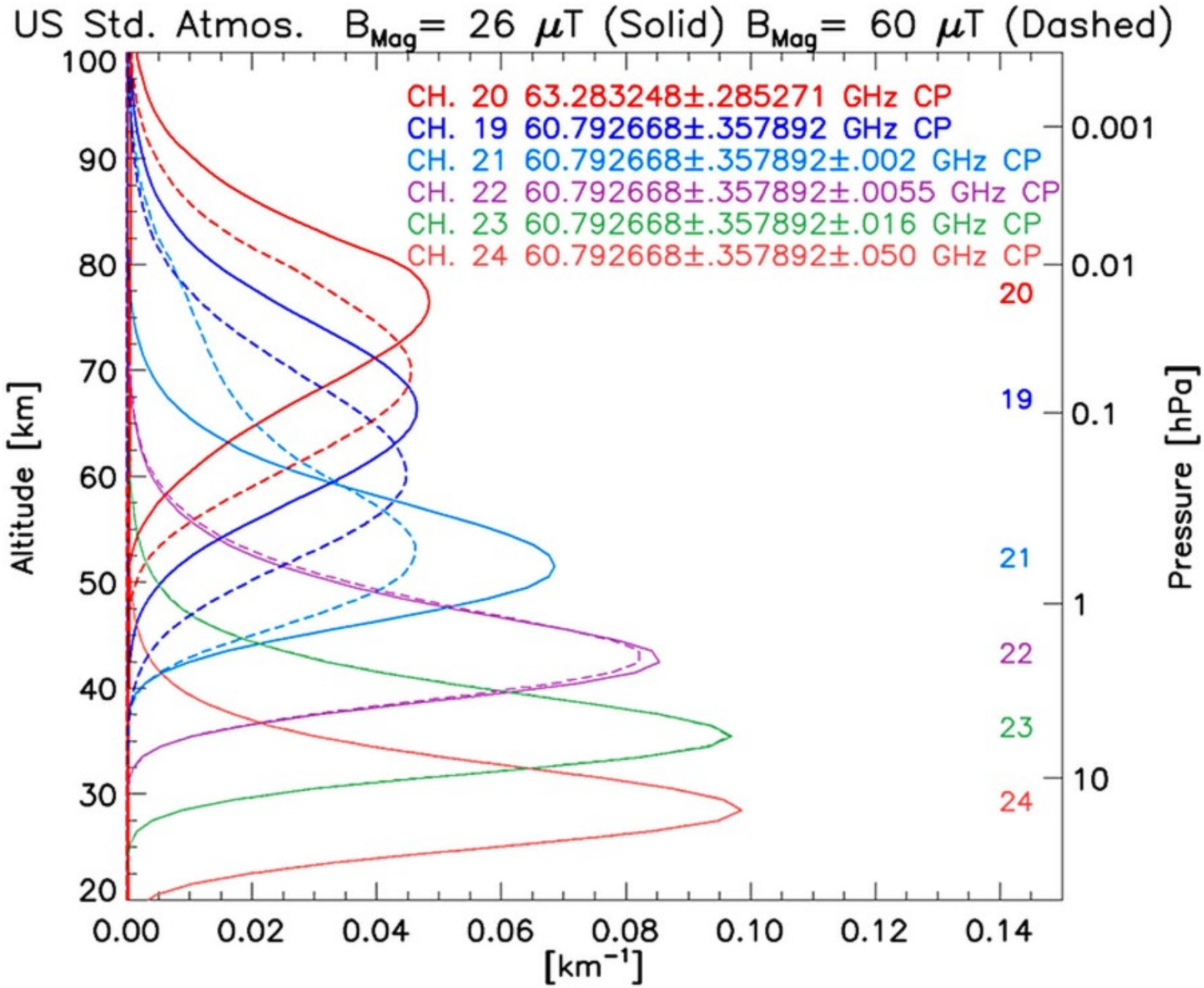
SSMIS Thermal UAS Channels



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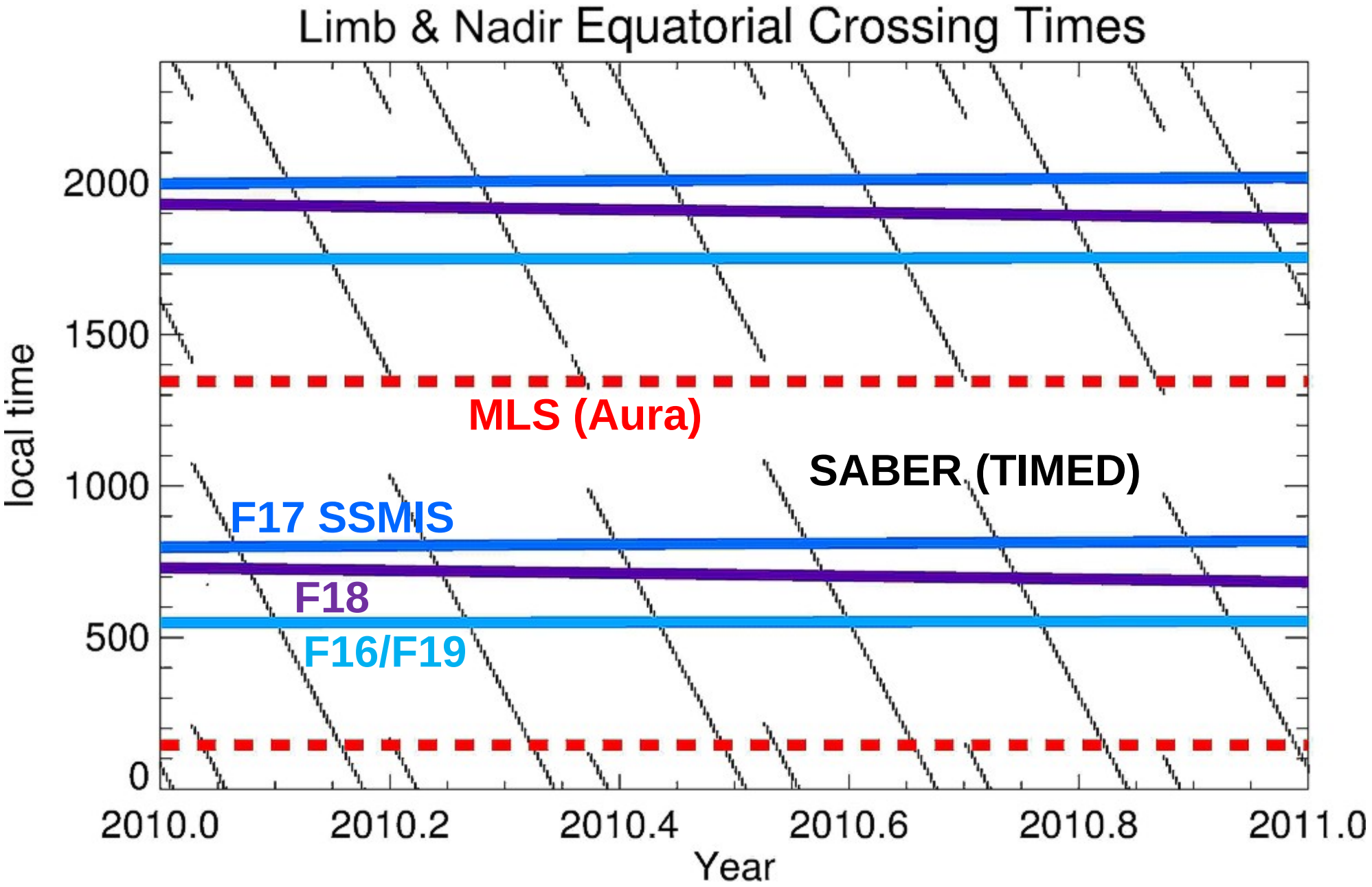
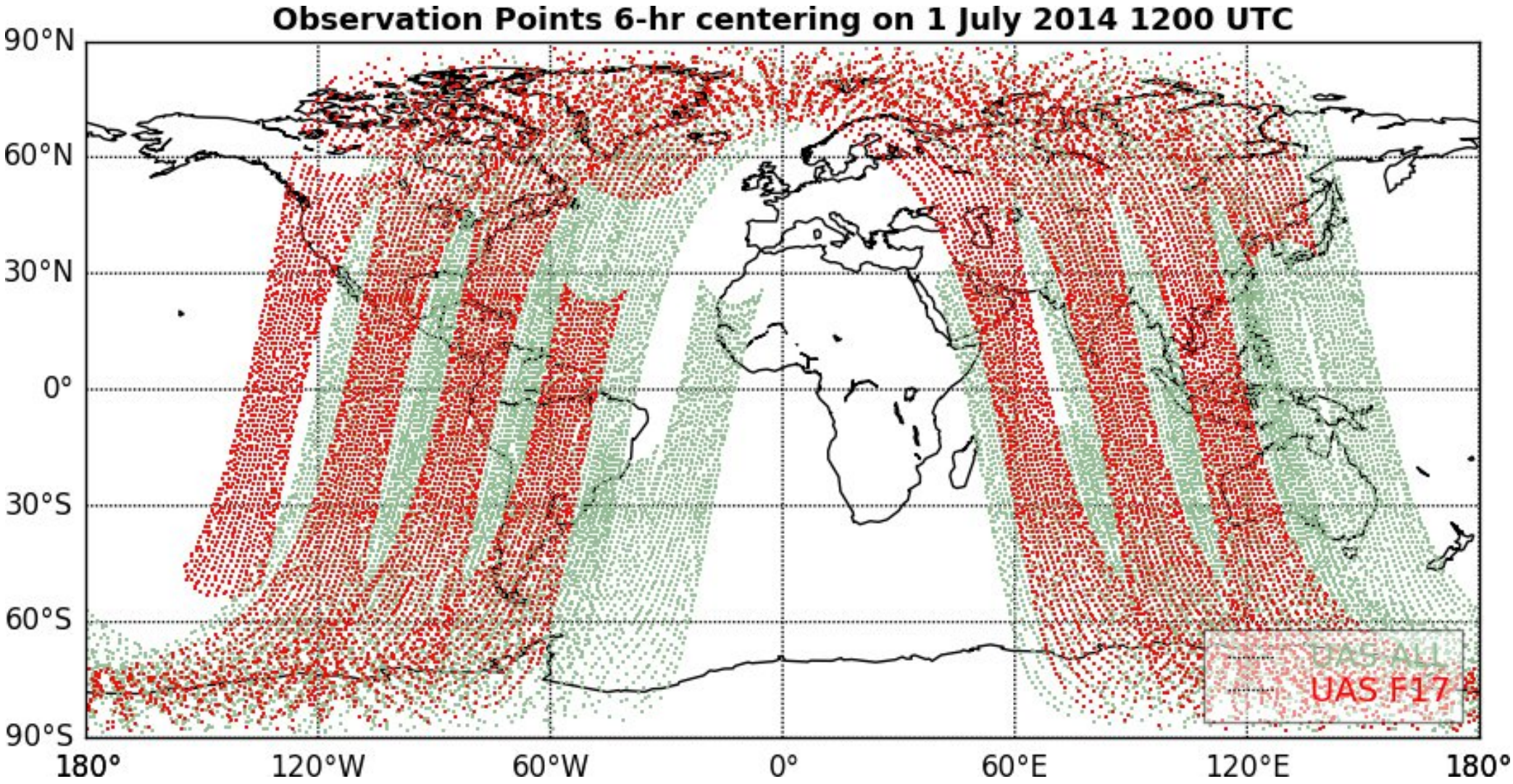
Local Time Coverage in the MLT



MLT Observational Sampling Every 6 Hours

SSMIS UAS F17 SSMIS UAS all



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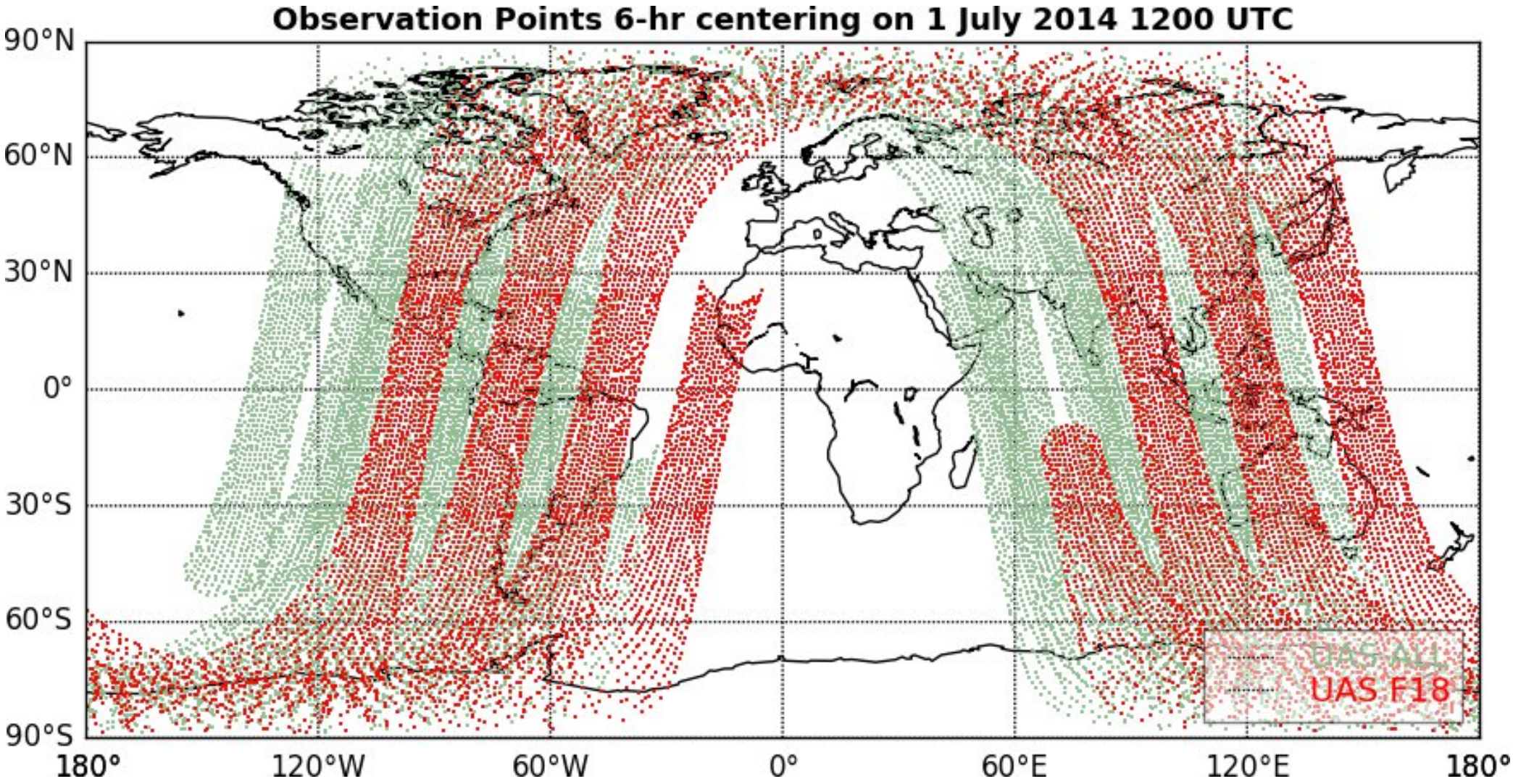
MLT Observational Sampling Every 6 Hours

SSMIS UAS F18

SSMIS UAS all



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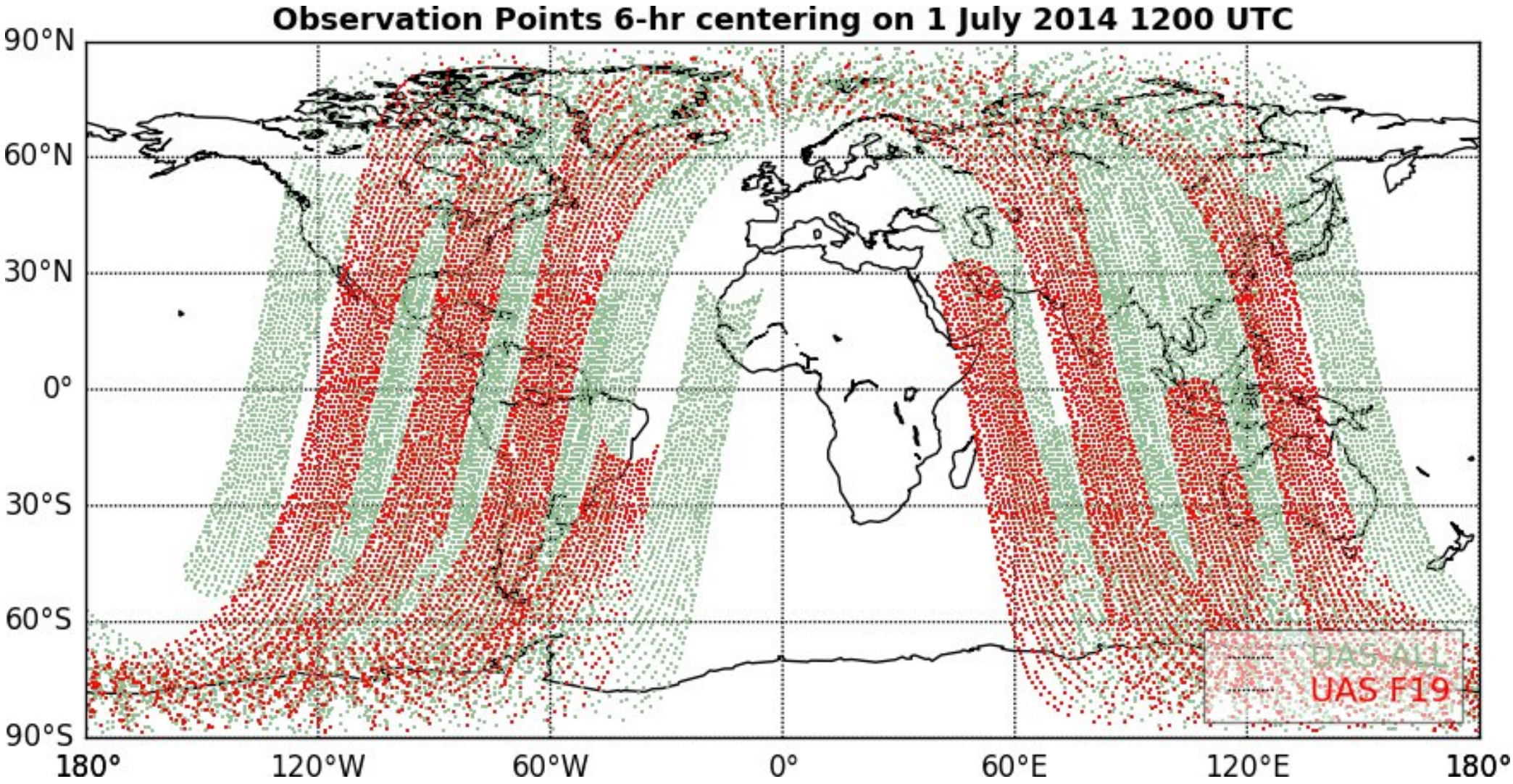
MLT Observational Sampling Every 6 Hours

SSMIS UAS F19 SSMIS UAS all



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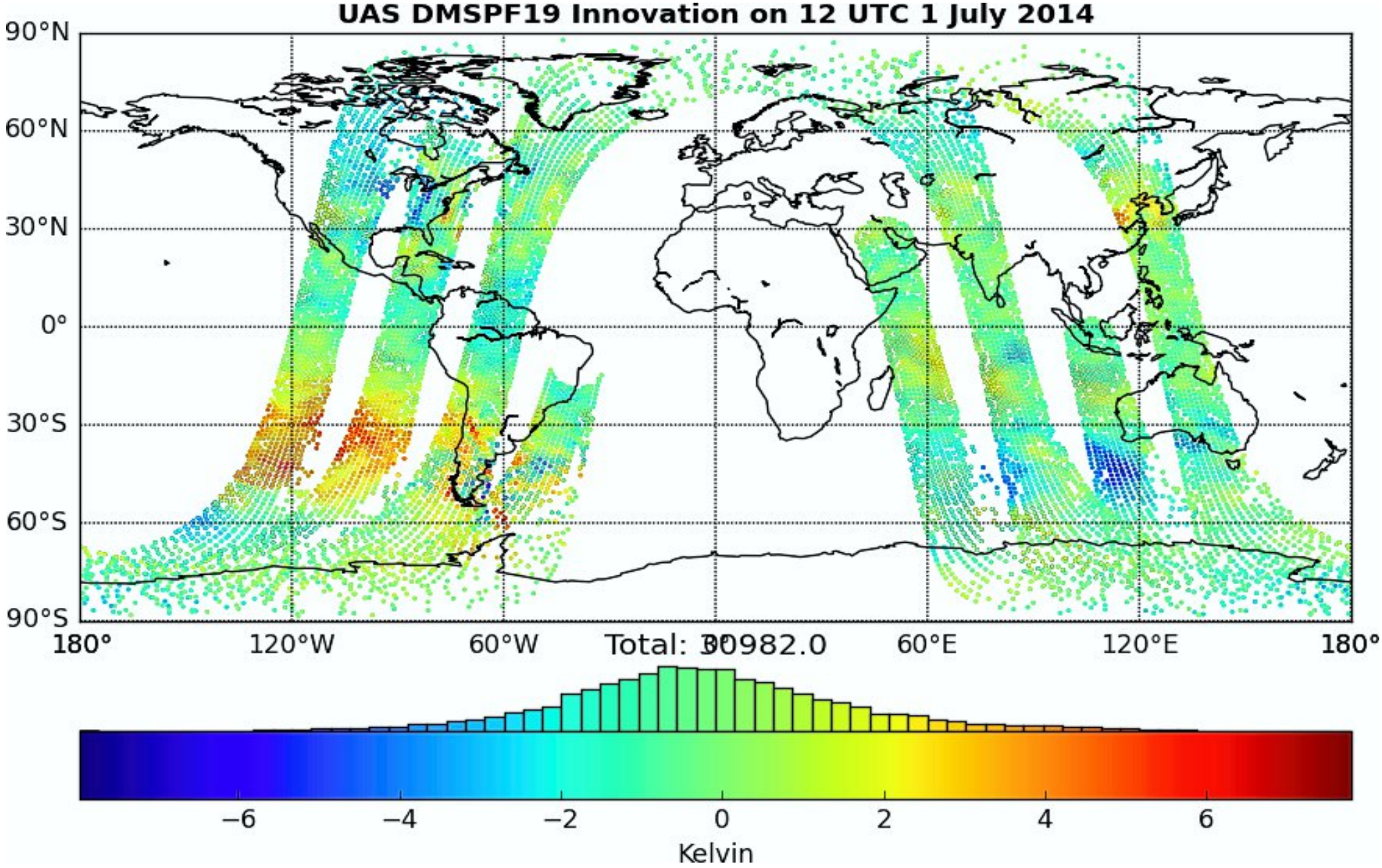
Sample Channel 20 SSMIS UAS Innovations



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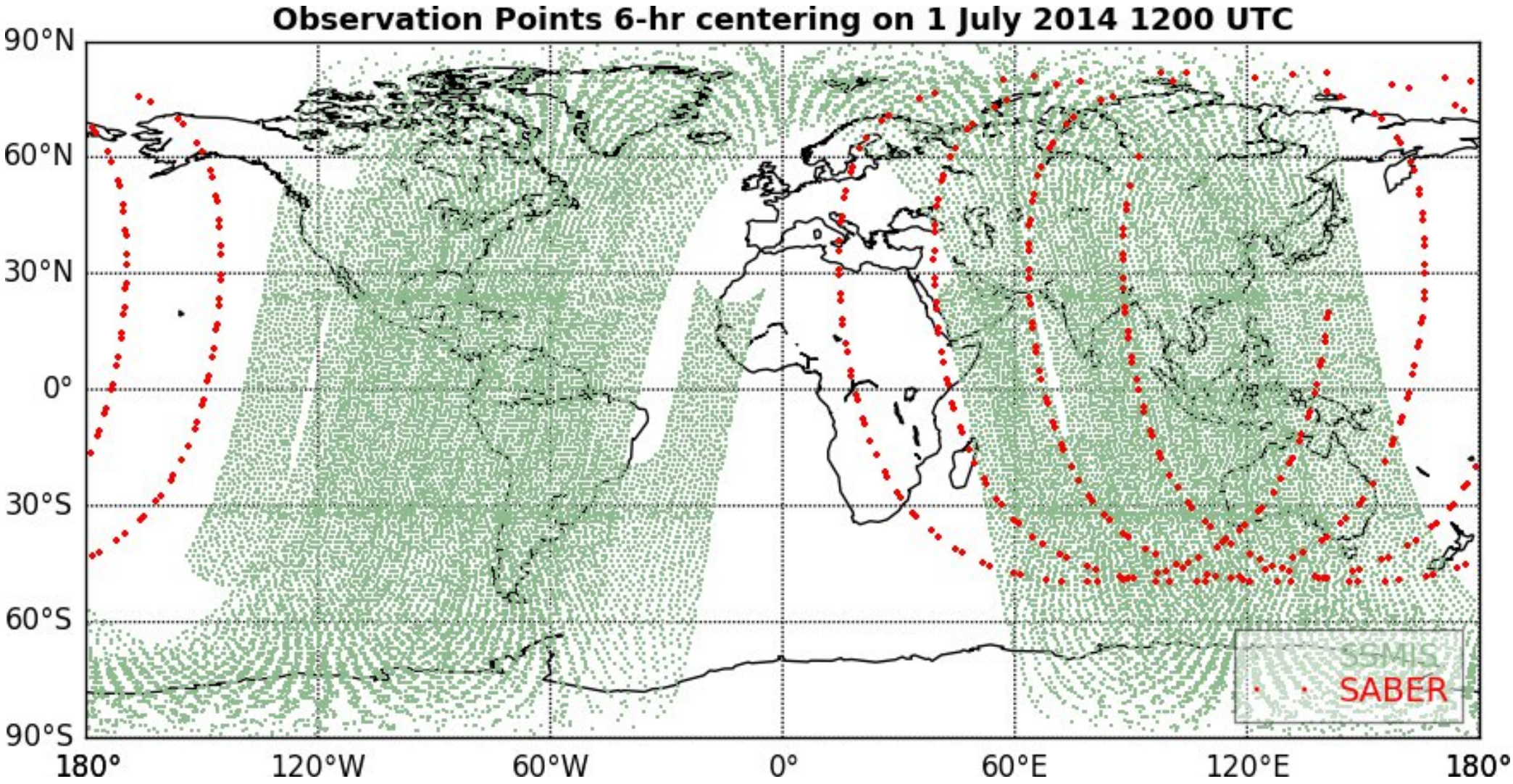
MLT Observational Sampling Every 6 Hours

SSMIS UAS + SABER



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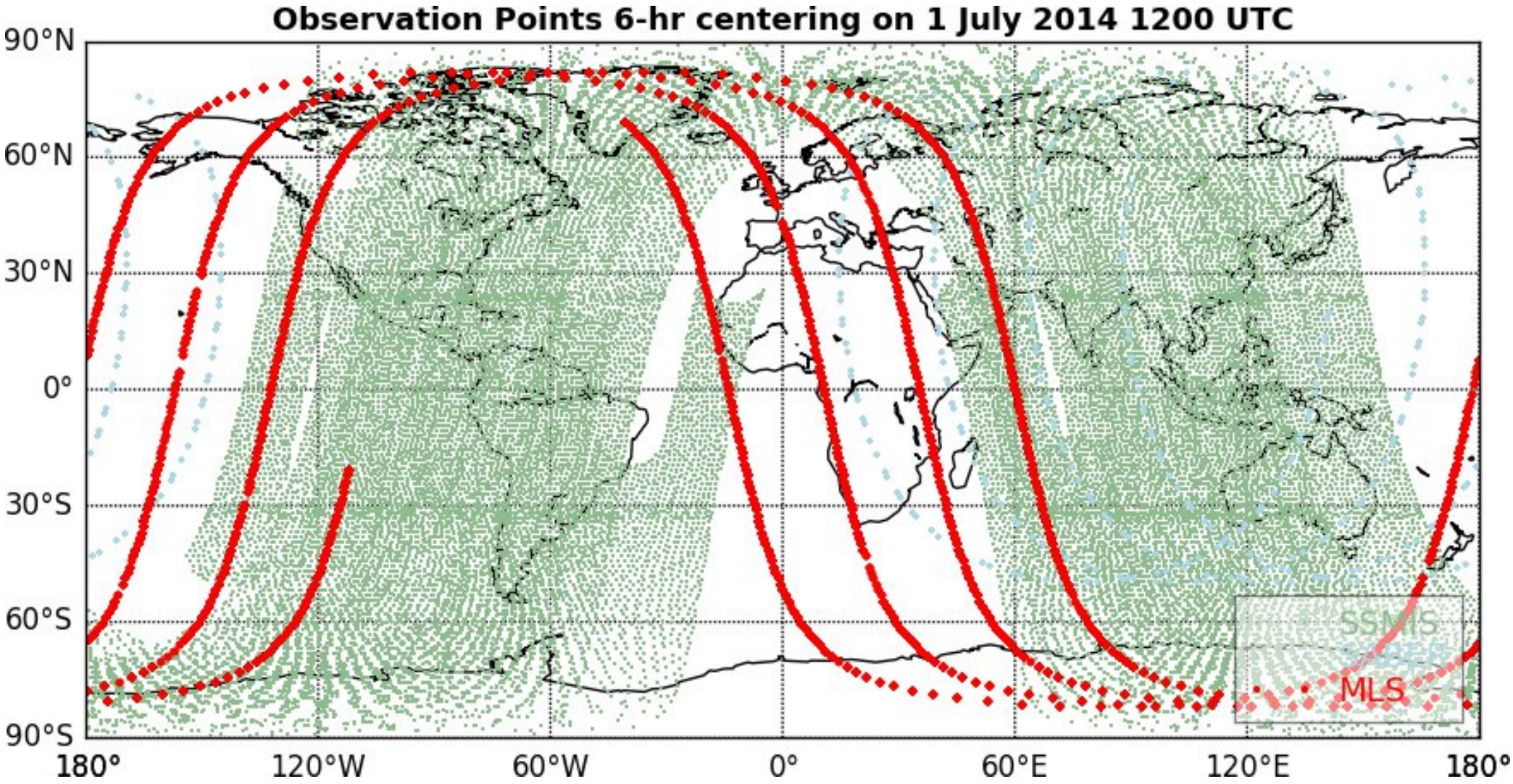
MLT Observational Sampling Every 6 Hours

SSMIS UAS + SABER + MLS



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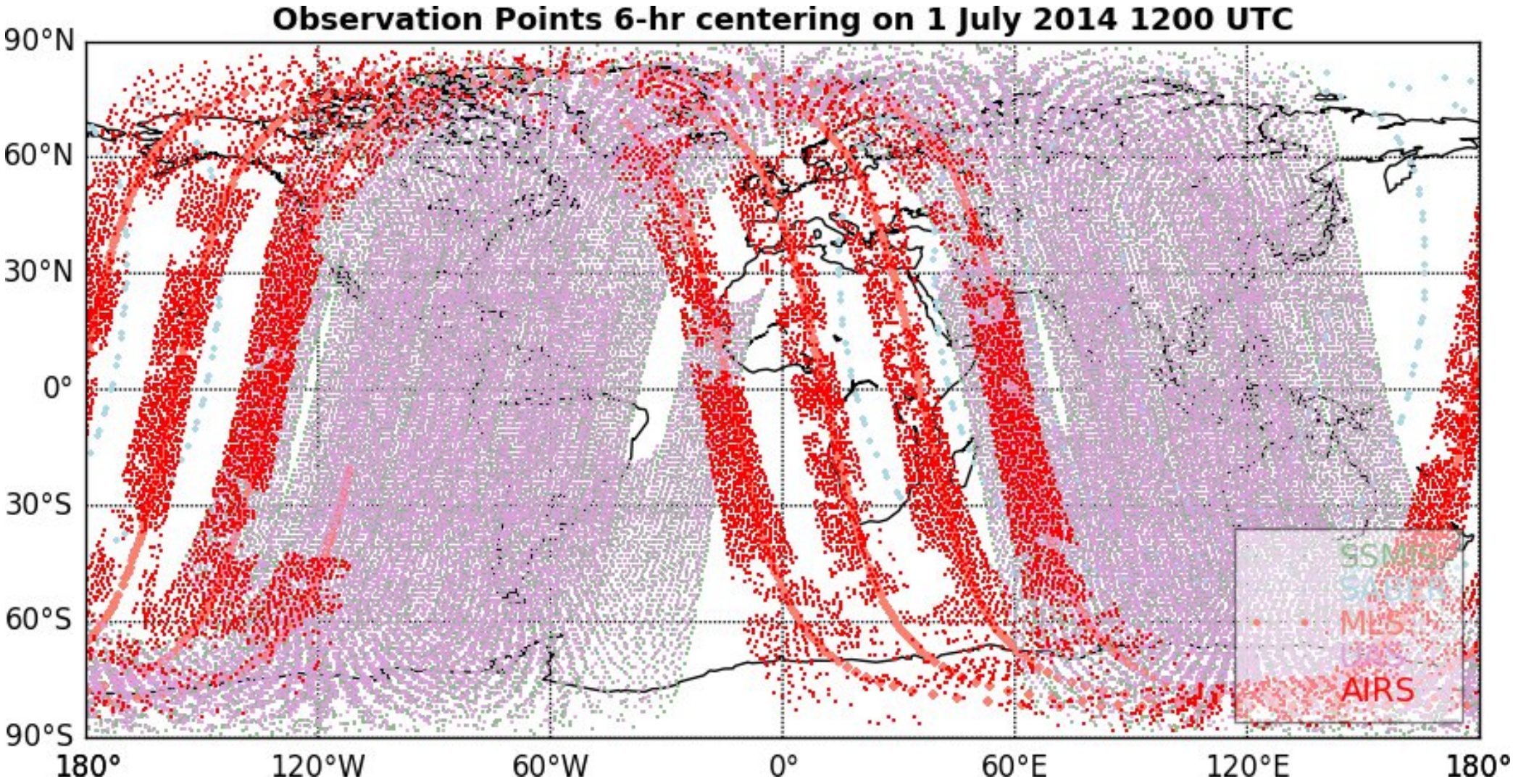
MLT Observational Sampling Every 6 Hours

SSMIS UAS + SABER + MLS + AIRS



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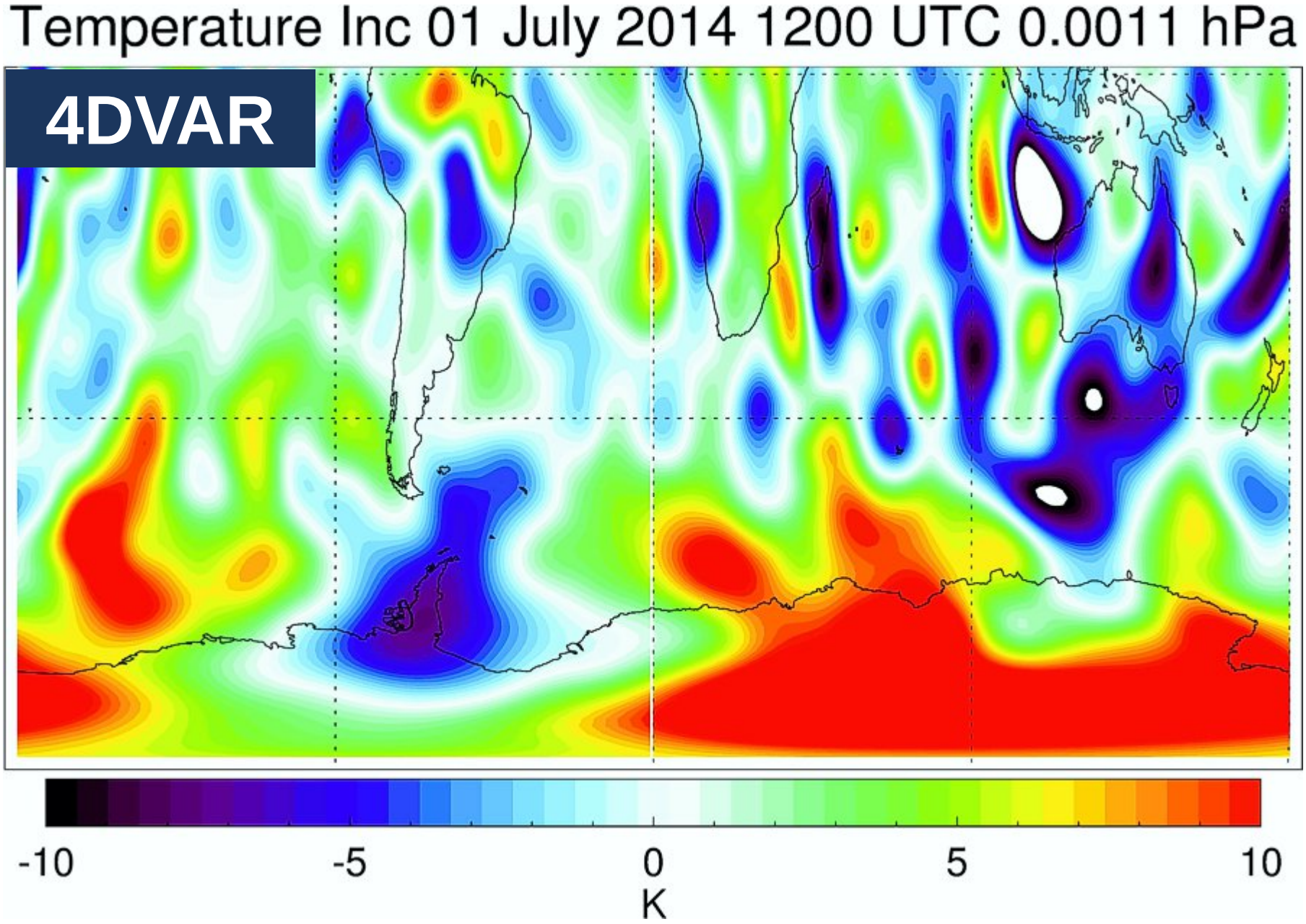
Sample MLT Temperature Increments



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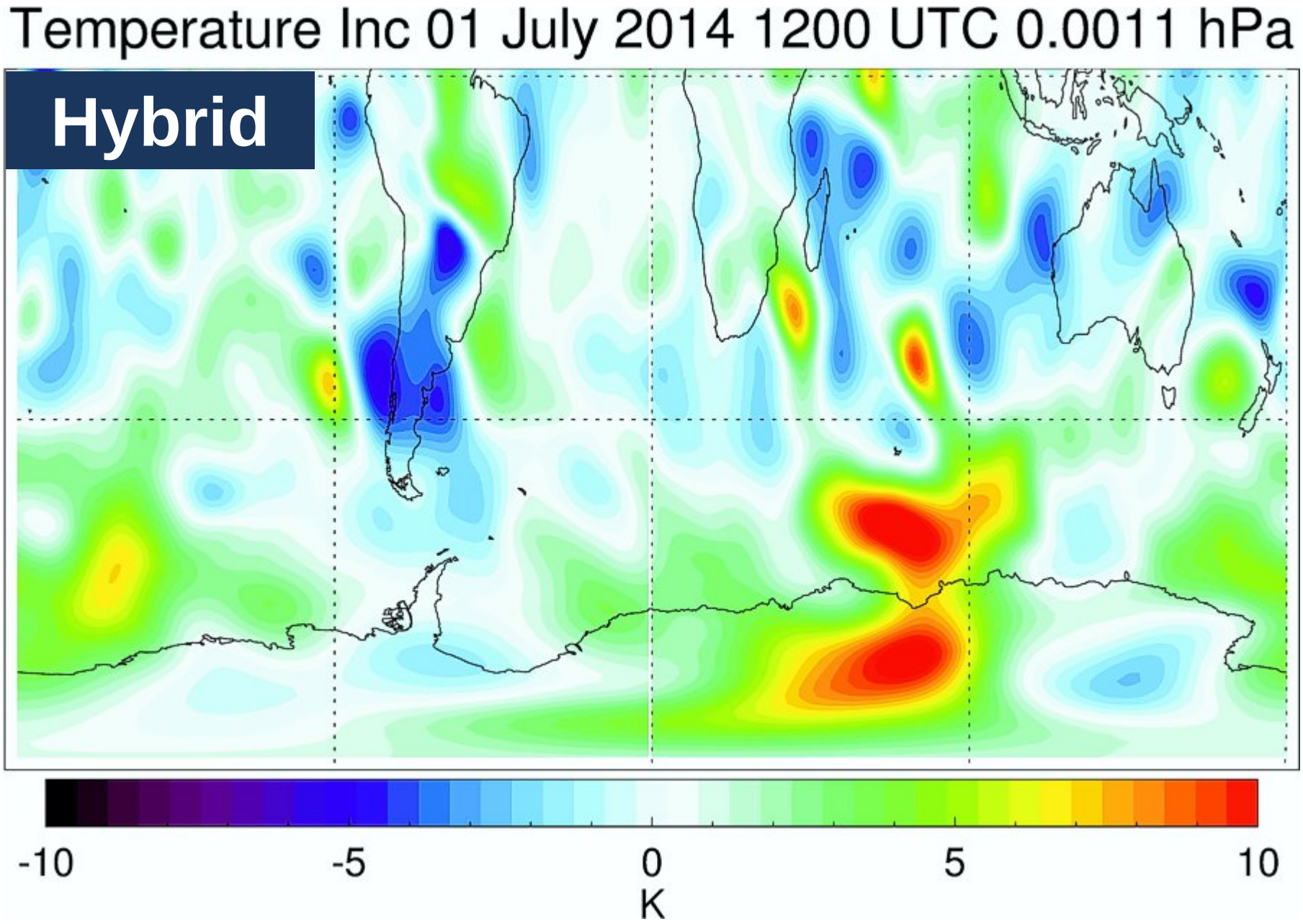
Sample MLT Temperature Increments



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NAVGEM DEEPWAVE Reanalysis

Wind Increments and "Missing" Gravity Wave Drag

Zonal Wind Increments and "Missing" GWD

- Several recent studies have argued that zonal-mean zonal-wind increments in the extratropical austral winter stratosphere reveal "missing" GWD in models (Orr et al. J. Clim. 2010; McLandress et al. JAS 2012; Kruse et al. JAS 2016)
- In particular, McLandress et al. (2012) argued that systematic negative (westward) increments at ~60ºS during austral winter indicated a missing source of GWD in models, either from subantarctic islands in Southern Ocean or meridional refraction of GWs into the vortex jet from higher and lower latitudes
- How does this work?

(1) Temperature increments specify zonal-mean zonal wind from meridional momentum balance

$$v_t + \frac{uv_\lambda}{a\cos\phi} + \frac{vv_\phi}{a} + fu + \frac{u^2\tan\phi}{a} + \frac{\Phi_\phi}{a} + wv_z + Y = 0,$$

geostrophic balance: $u = u_{gb} + \Delta u_{inc}$

(2) Zonal wind increments (corrections) in zonal momentum equation map to gravity-wave drag

$$u_t + \frac{uu_\lambda}{a\cos\phi} + \frac{v\,(u\cos\phi)_\phi}{a\cos\phi} - fv + \frac{\Phi_\lambda}{a\cos\phi} + wu_z + X = 0,$$

$\Delta u_{inc} / \Delta t$

zonal wind increments (bias) must be removed by a balancing GWD increment ΔX_{inc}, (mean v responds)

ΔX_{inc}

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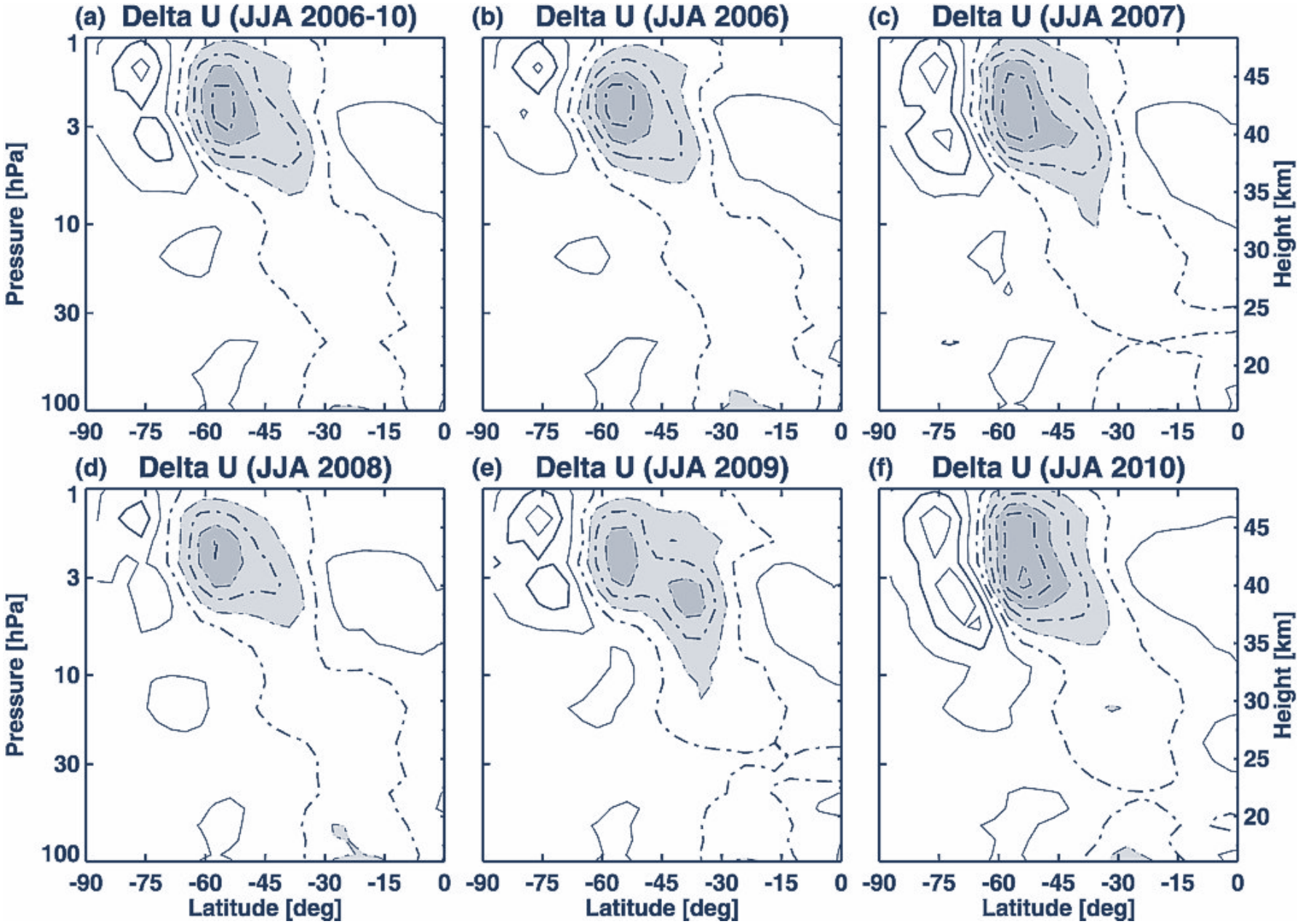
CMAM Zonal-Mean Zonal Wind Increments

(McLandress et al. JAS 2012)



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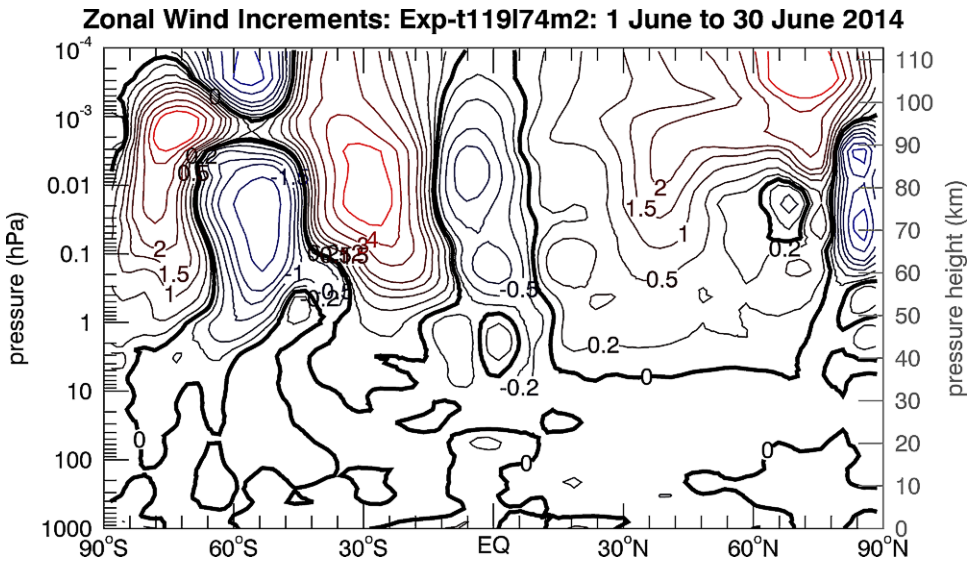
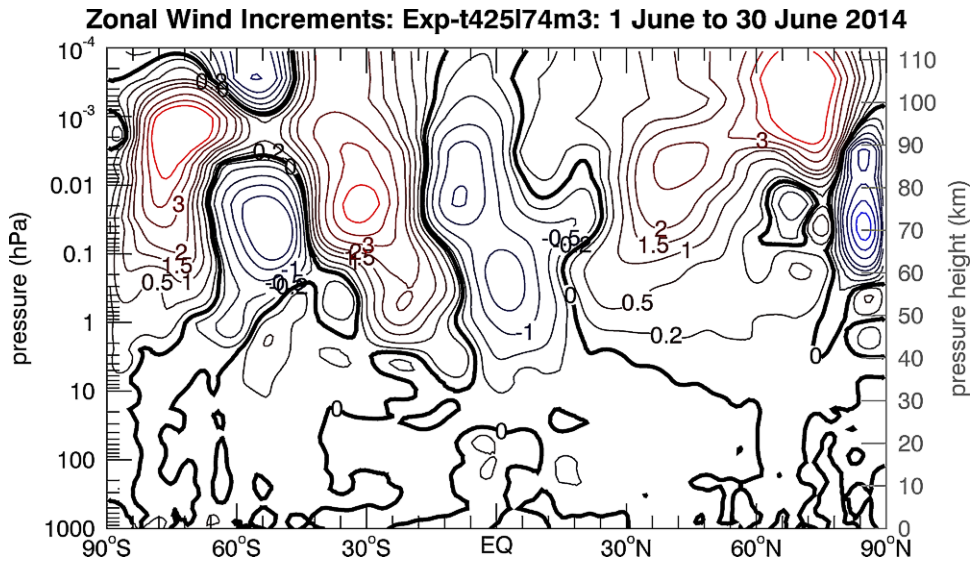
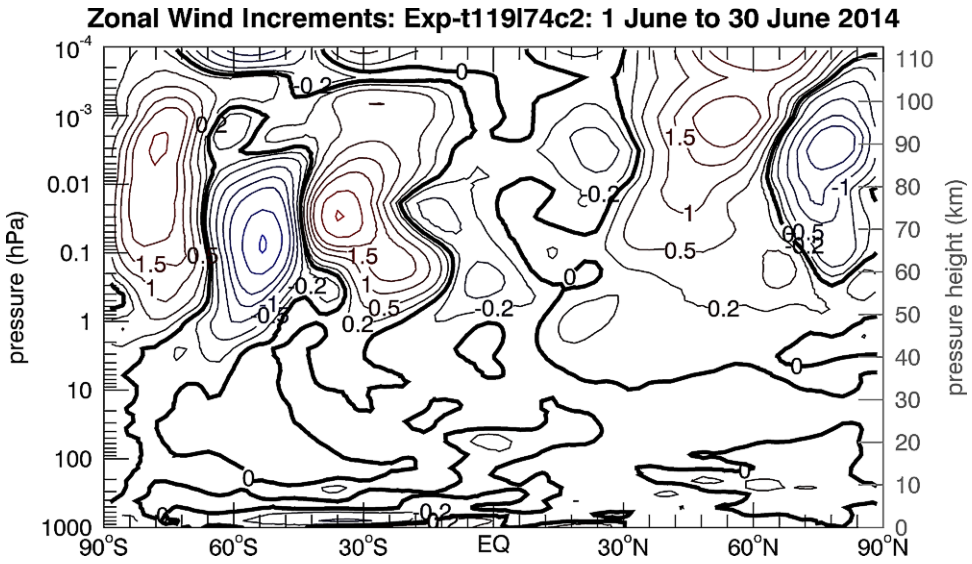
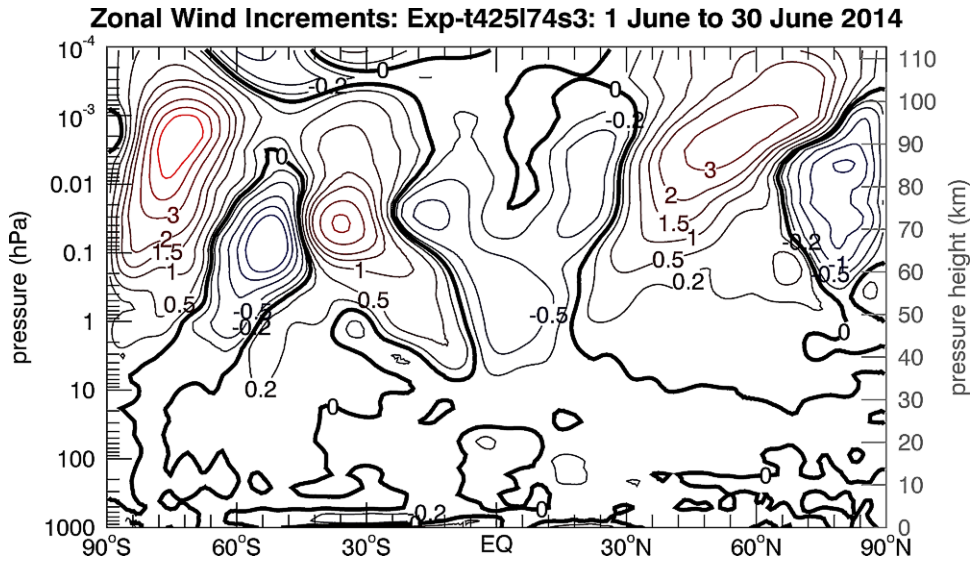
June Zonal-Mean Zonal-Wind Increments









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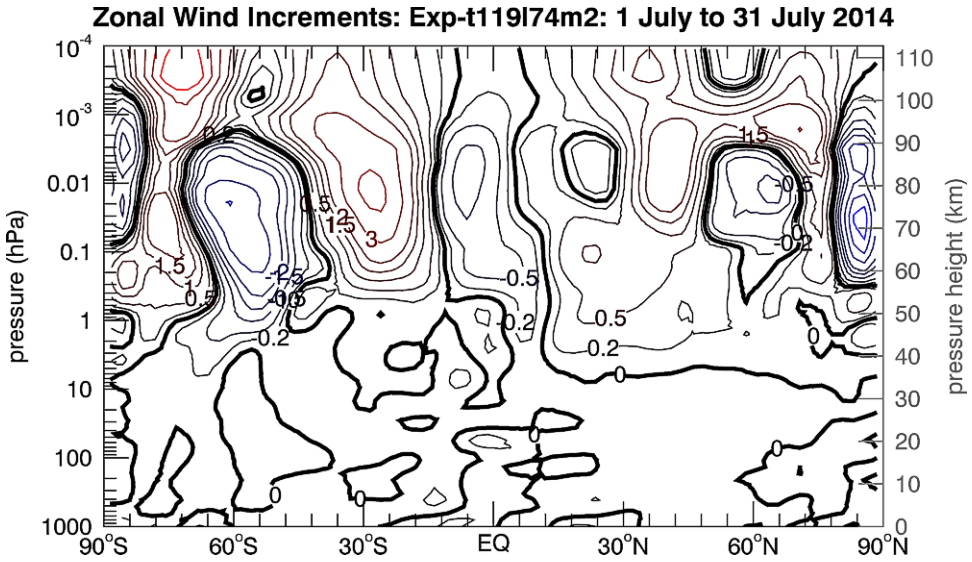
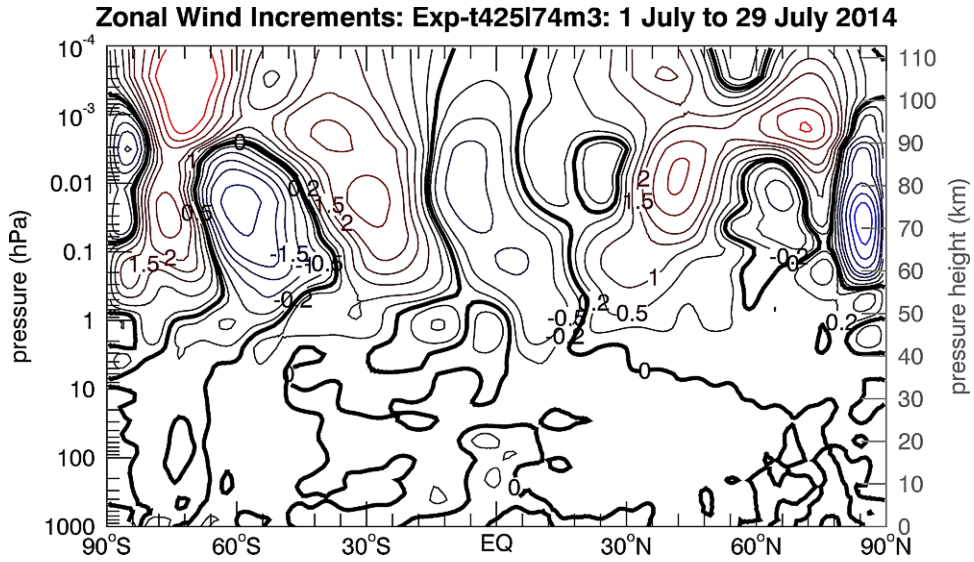
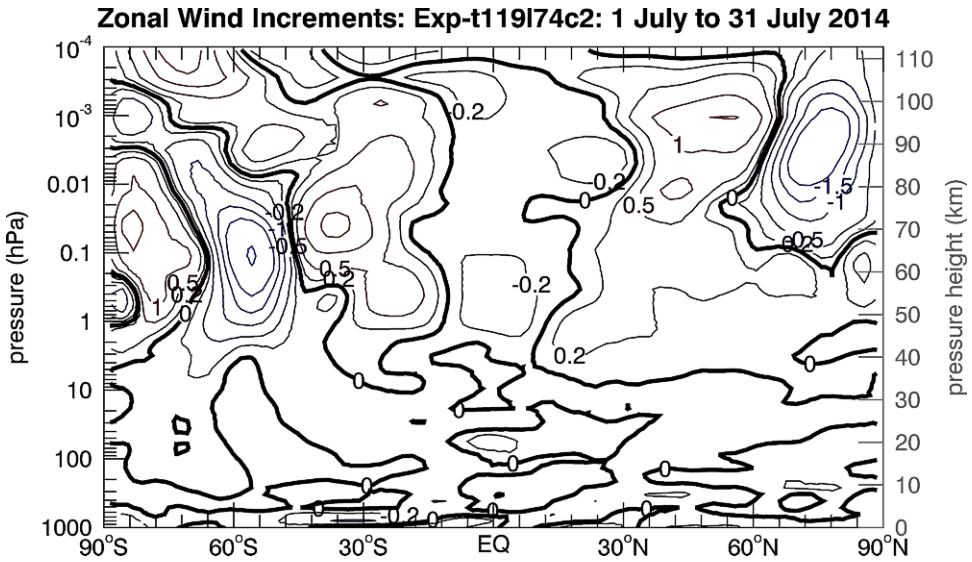
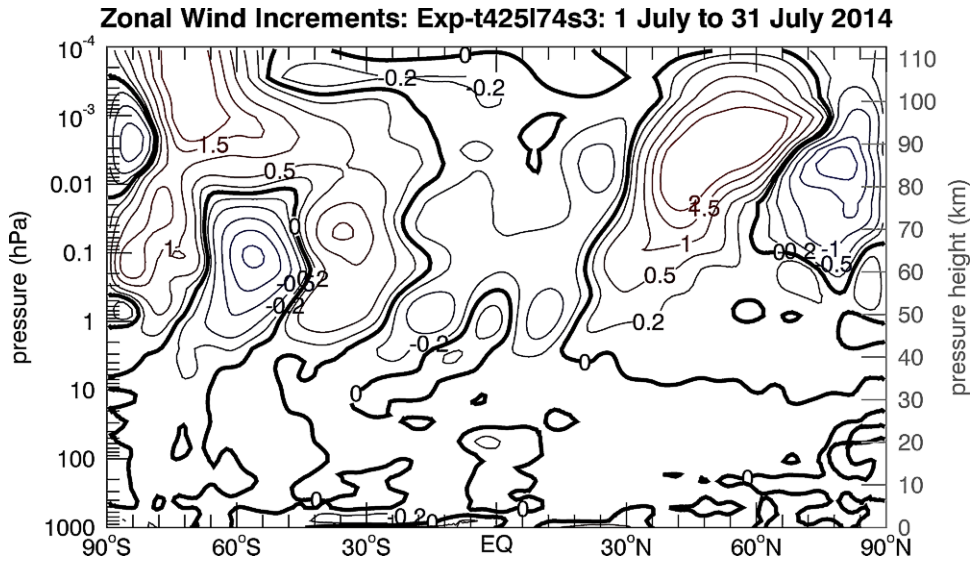
July Zonal-Mean Zonal-Wind Increments









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NAVGEM DEEPWAVE Reanalysis

Validation

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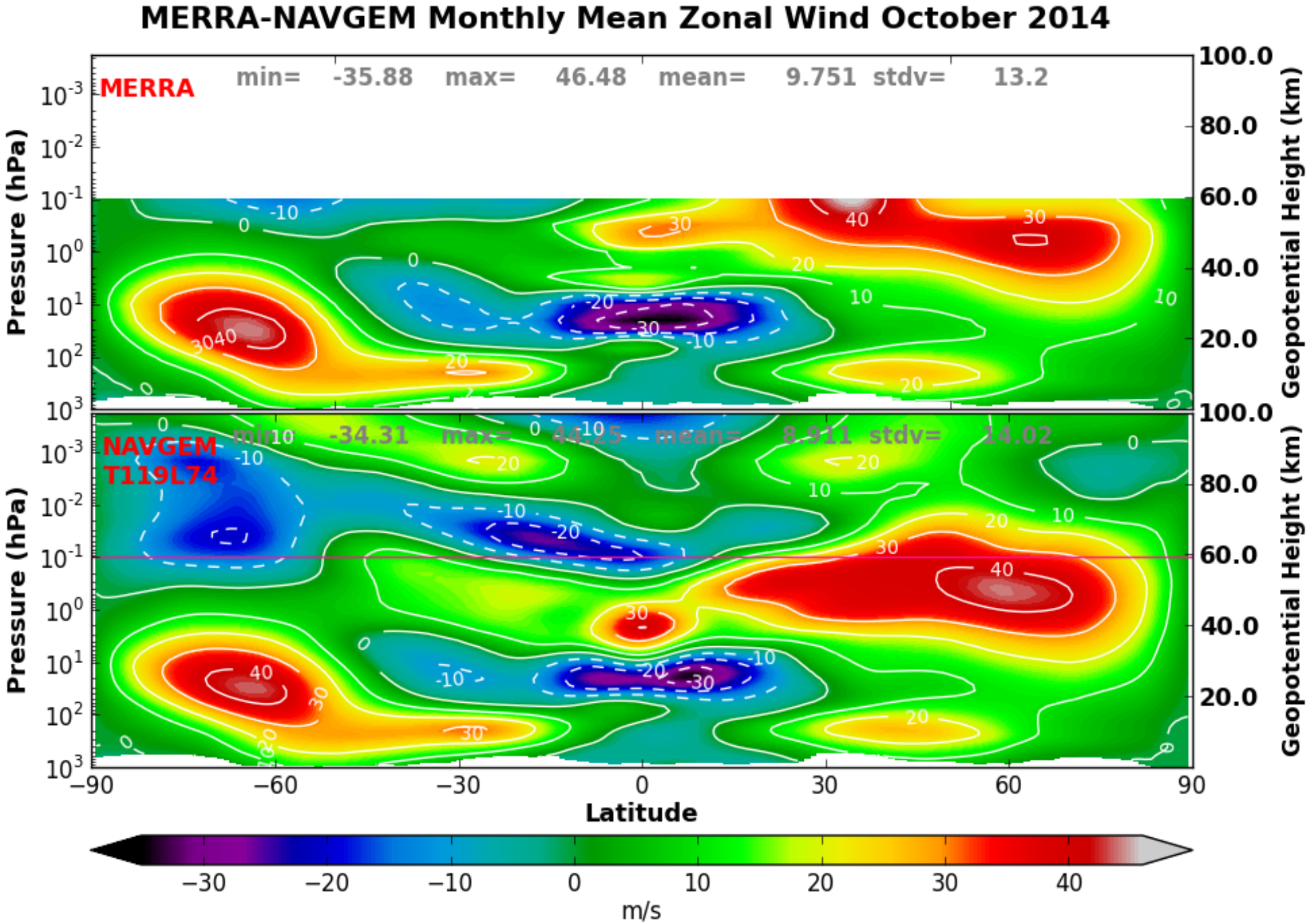
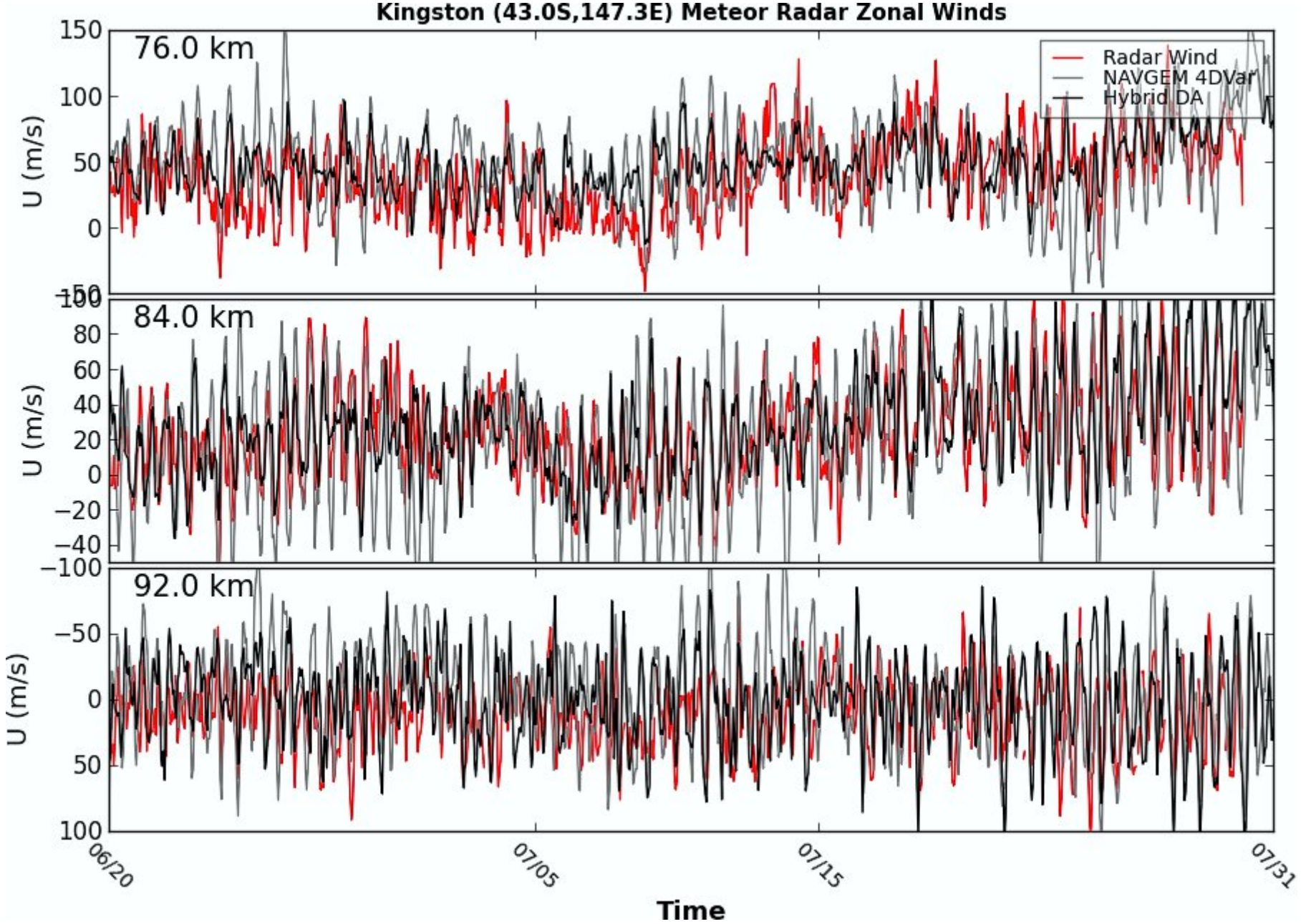
Mean Analysis Winds: 2014 Austral Winter
NAVGEM vs. NASA MERRA2



Meteor Radar in Kingston Tasmania MLT Zonal Winds



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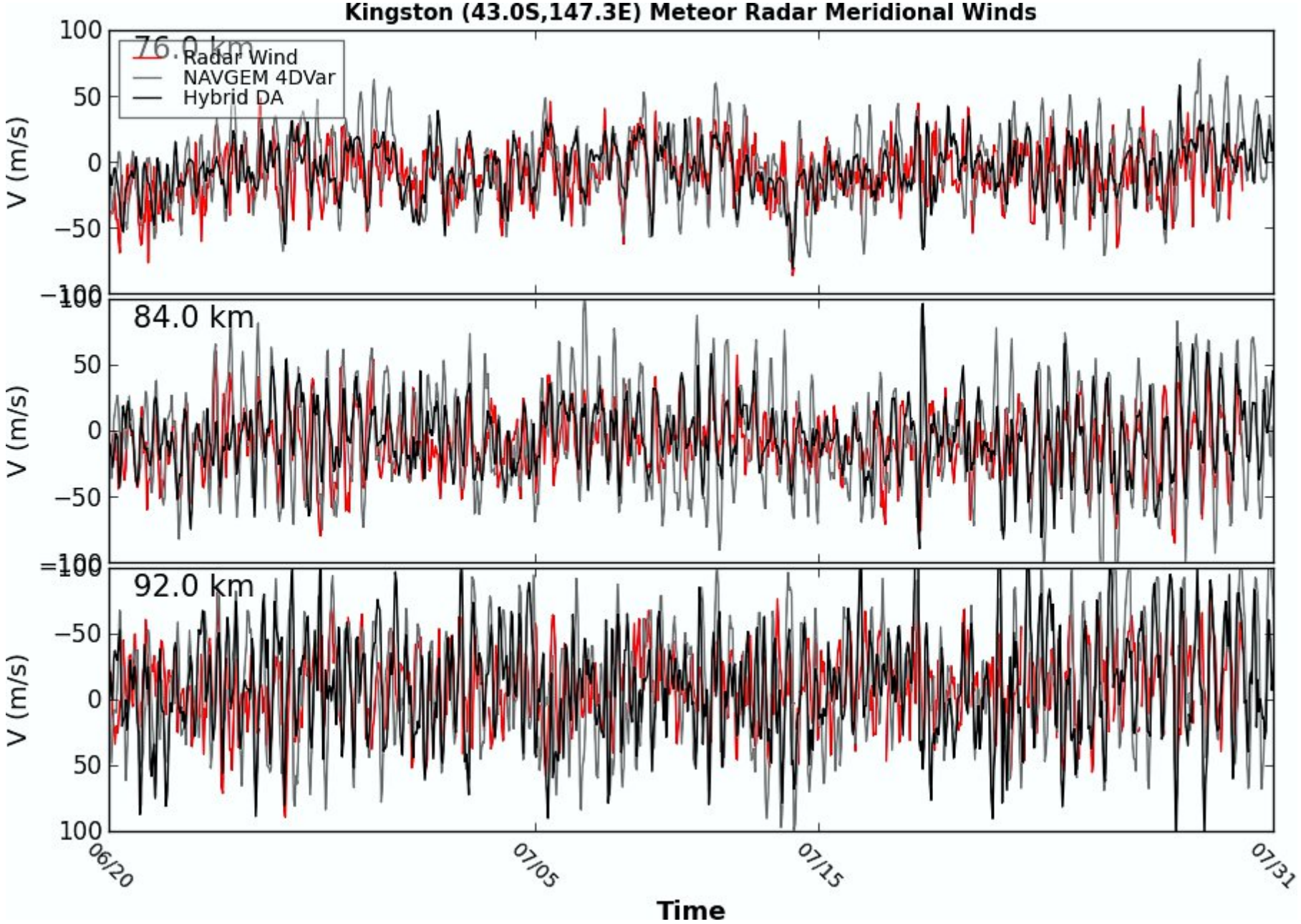
Meteor Radar in Kingston Tasmania MLT Meridional Winds



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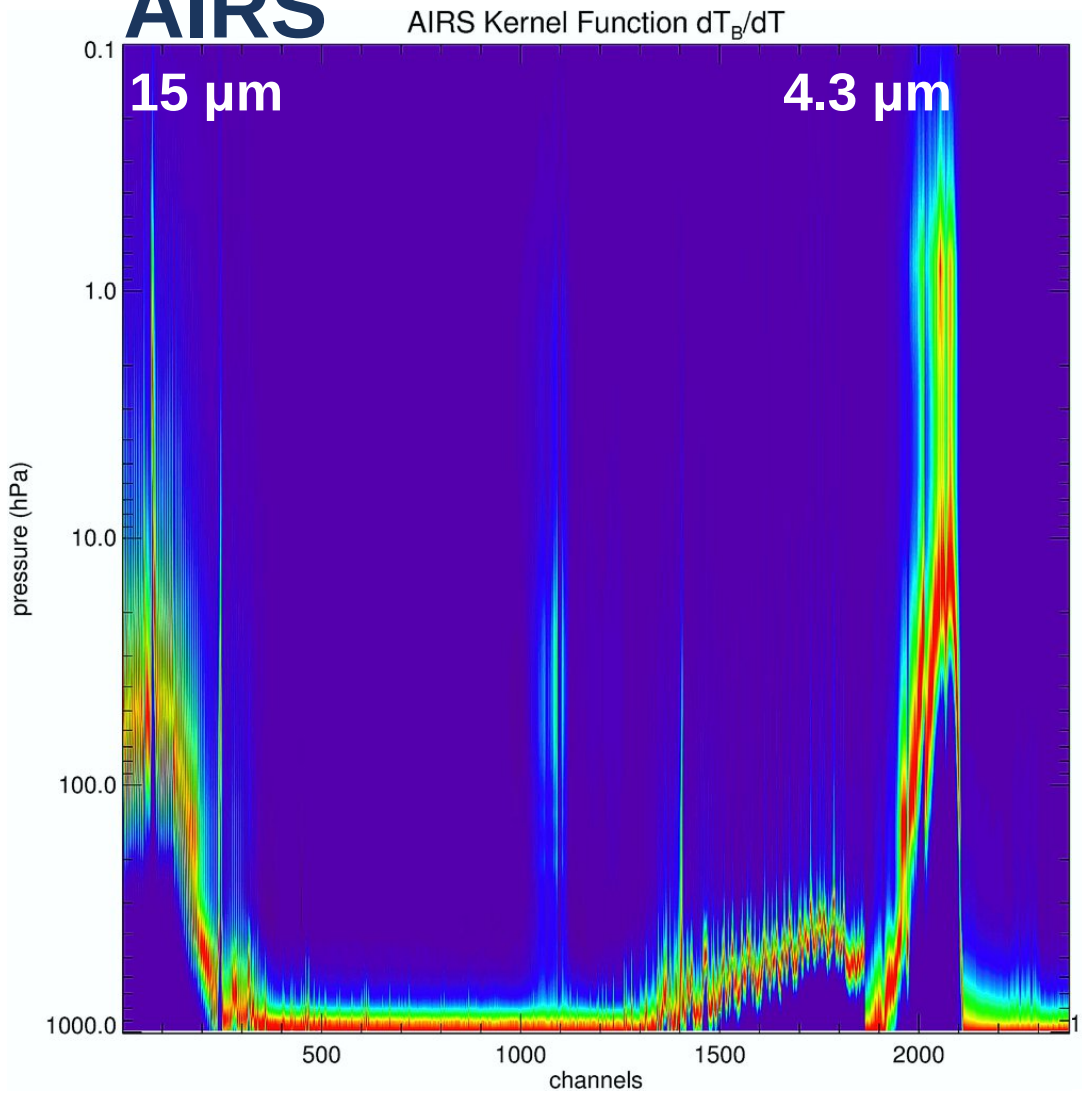
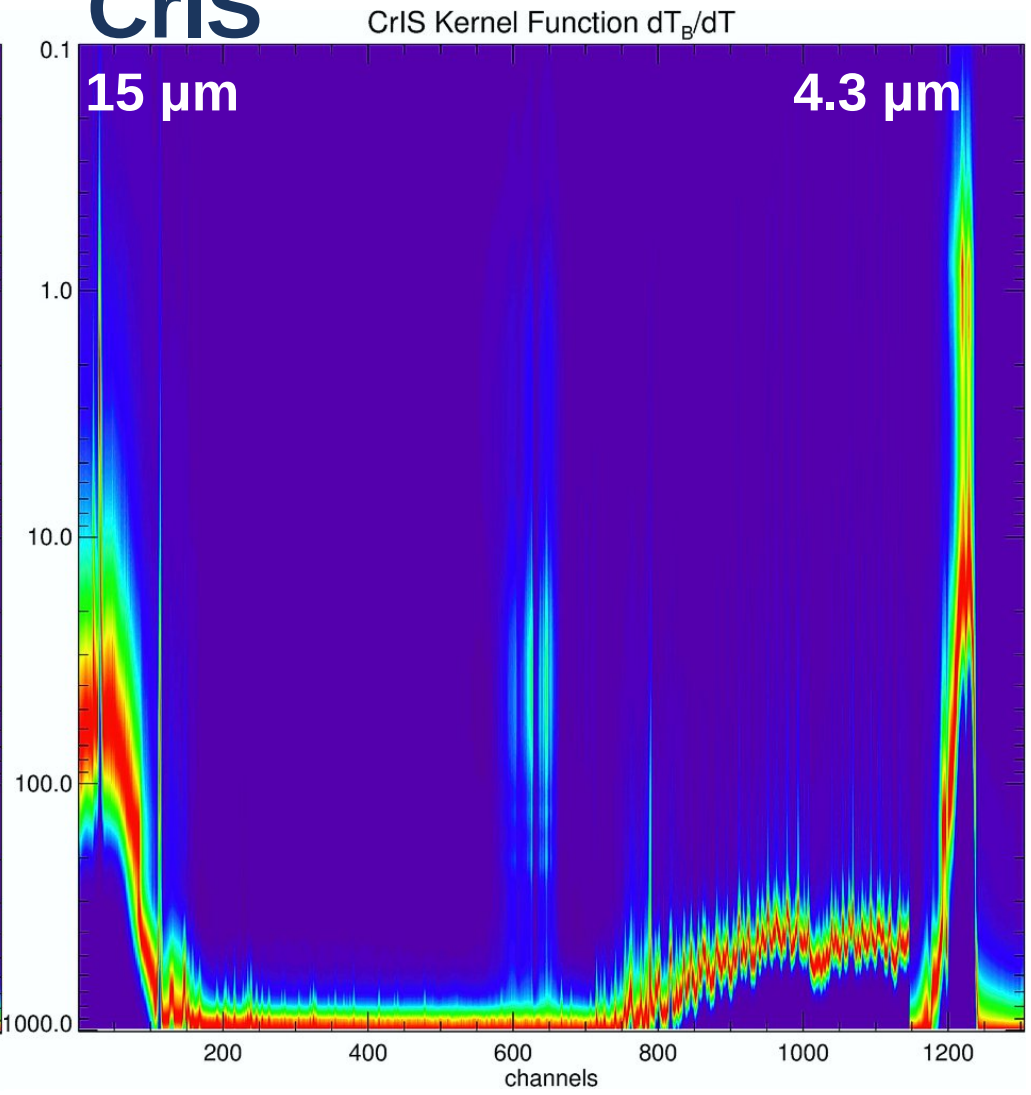
Deep Gravity-Wave Dynamics over the Auckland Islands and Macquarie Island during RF23

CRTM Temperature Kernels for AIRS and CrIS Channels: All Channels

AIRS



CrIS



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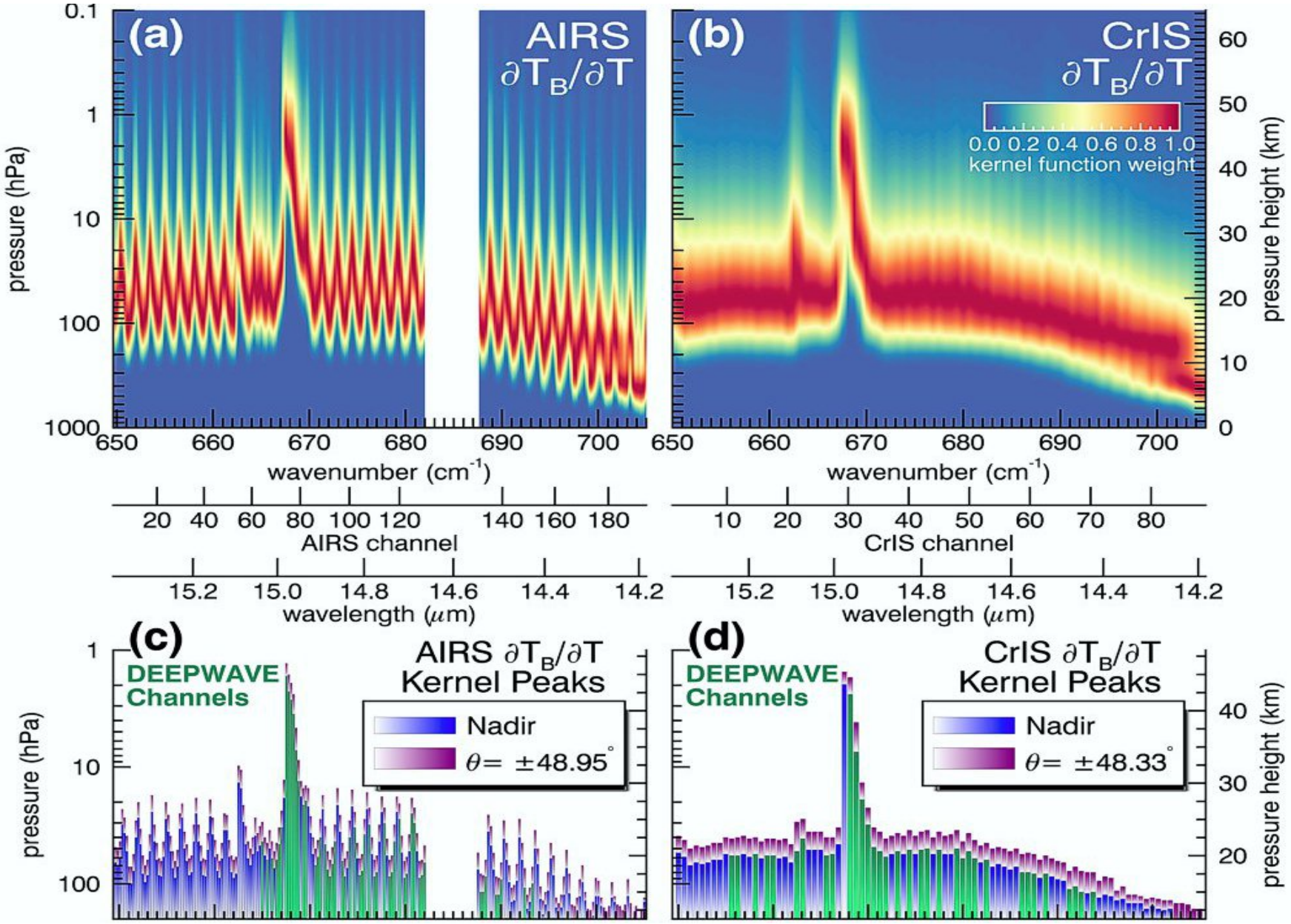
CRTM Temperature Kernels for AIRS and CrIS Channels in ~15 μm CO_2 IR Bands



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AIRS and CrIS Mean-Altitude Channels

AIRS

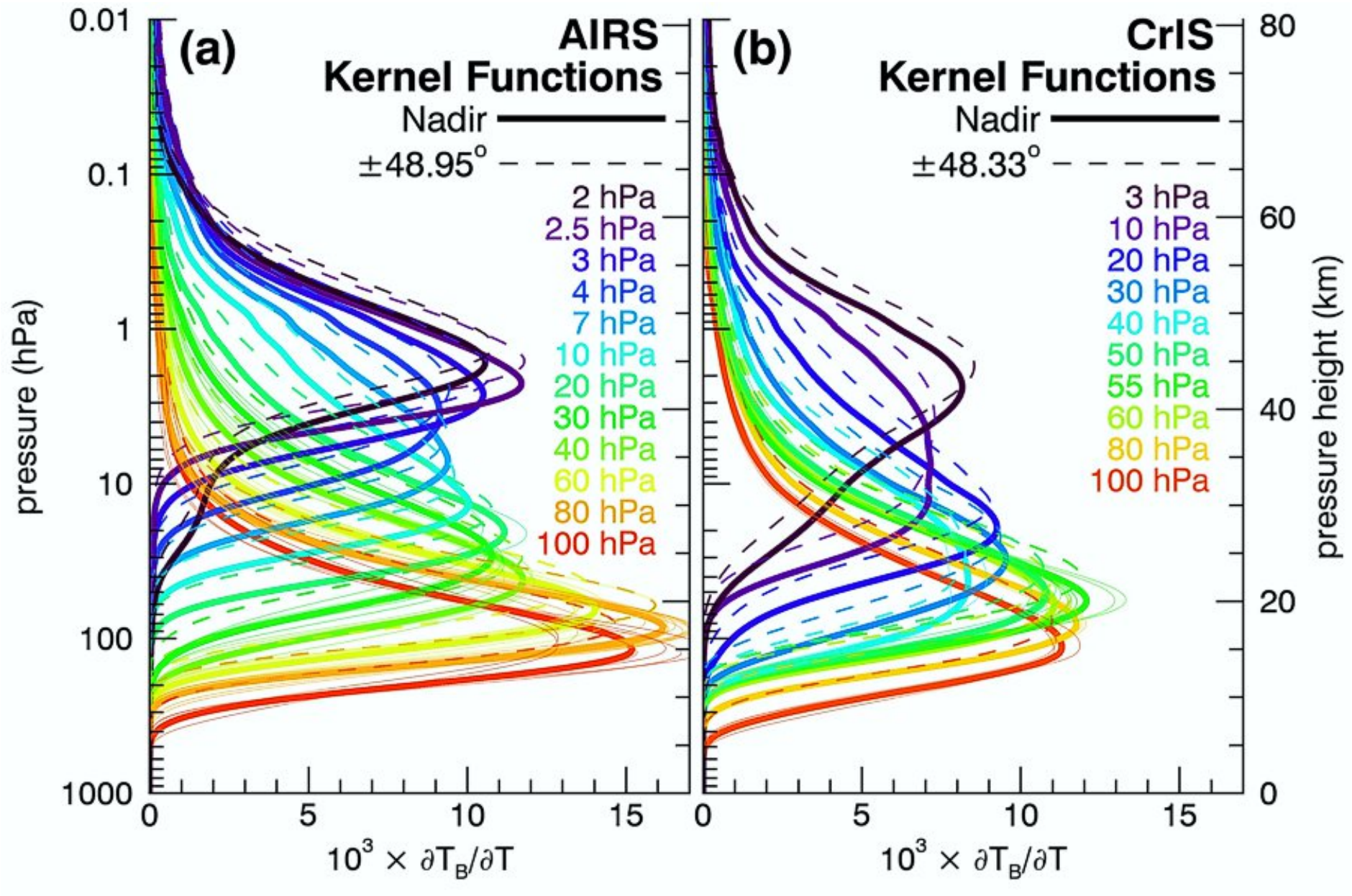
Mean Channel Number j	Pressure Peak (hPa)	Pressure Height (km)	No. of AIRS Channels N_j	AIRS Channel Numbers i	ν_i (cm^{-1})
1	2	43.5	1	74	667.530
2	2.5	42.0	1	75	667.782
3	3	40.5	1	76	668.035
4	4	38.5	1	77	668.288
5	7	35.0	1	78	668.541
6	10	32.0	1	79	668.795
7	20	27.0	2	81, 82	669.302, 669.556
8	30	24.5	6	102, 108, 114, 120, 125, 126	674.680, 676.233, 677.794, 679.362, 680.675, 680.938
8β	30	24.5	1	72	667.025
9	40	22.5	7	64, 88, 90, 94,100, 106, 118	665.015, 671.085, 671.596, 672.621, 674.164, 675.715, 678.839
9β	40	22.5	1	71	666.773
10	60	19.5	9	66, 68, 70, 86, 87, 91, 93, 97, 130	665.516, 666.018, 666.521, 670.575, 670.830, 671.852, 672.364, 673.392,681.993
11	80	17.5	14	92, 98, 104, 105, 110, 111, 116, 117, 122, 123, 128, 129, 134, 140	672.108, 673.649, 675.197, 675.456, 676.753, 677.013, 678.316, 678.577, 679.887, 680.149, 681.465, 681.729, 688.410, 690.033
12	100	16.0	6	132, 133, 138, 139, 149, 152	687.871, 688.140, 689.491, 689.762, 692.482, 693.302
13	~5	~36	XX	xxxx-xxxxx xxxx-xxxx	~4.3 μm

CrIS

Mean Channel Number j	Pressure Peak (hPa)	Pressure Height (km)	No. of CrIS Channels N_j	CrIS Channel Numbers i	ν_i (cm^{-1})
1	3	40.5	1	30	668.125
2	10	32.0	1	31	668.750
3	20	27.0	1	32	669.375
4	30	24.5	1	33	670.000
5	40	22.5	2	21, 22	662.500, 663.125
6	50	21.0	9	34, 35, 38, 40, 42, 43, 45, 48, 50	671.250, 671.875, 673.750, 675.000, 676.250, 676.875, 678.125, 680.000, 681.250
6β	55	20.5	7	10, 11, 14, 16, 17, 26, 27	655.625, 656.250, 658.125, 659.375, 660.000, 665.625, 666.250
7	60	19.5	4	36, 49, 51, 53	671.875, 680.000, 681.250, 682.500
8	80	17.5	4	59, 60, 61, 63	686.250, 686.875, 687.500, 688.750
9	100	16.0	4	67, 68, 69, 71	691.250, 691.875, 692.500, 693.750
10	~5	~36	16	1214-1223 1226-1231	~4.3 μm

← following, e.g., Hoffmann and Alexander (JGR 2013)

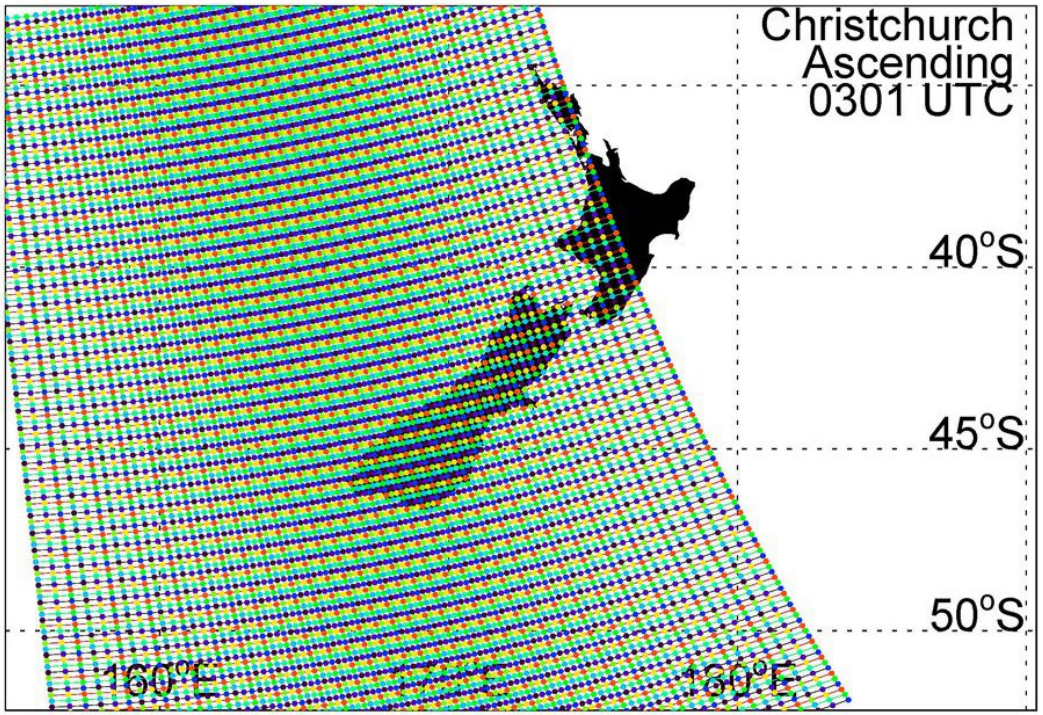
CRTM Temperature Kernel Functions of Mean-Altitude Channels



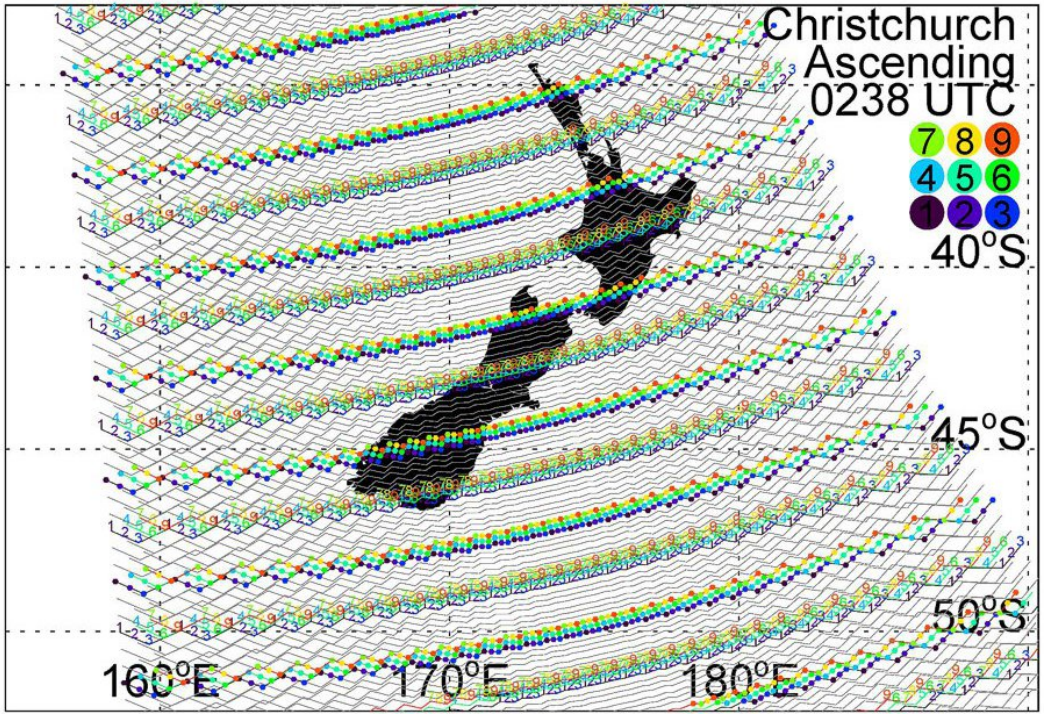
Different Cross-Track Sampling Patterns

Ascending 22 June 2014

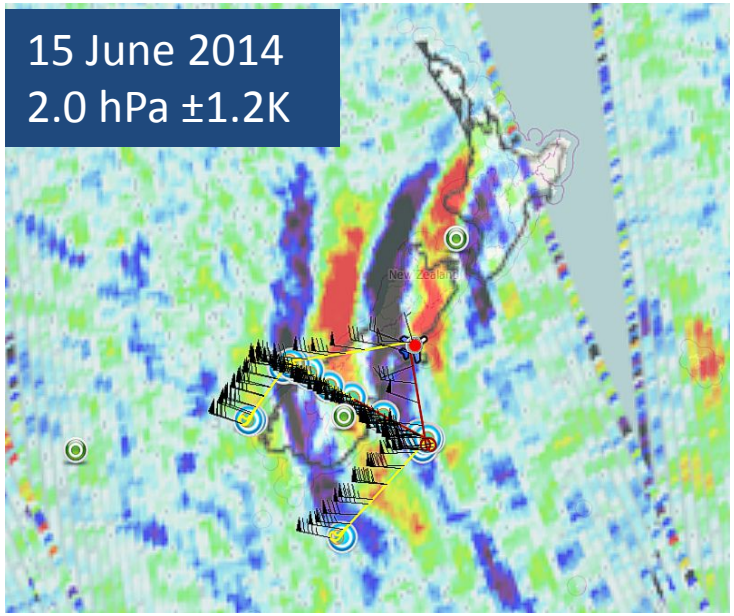
AIRS

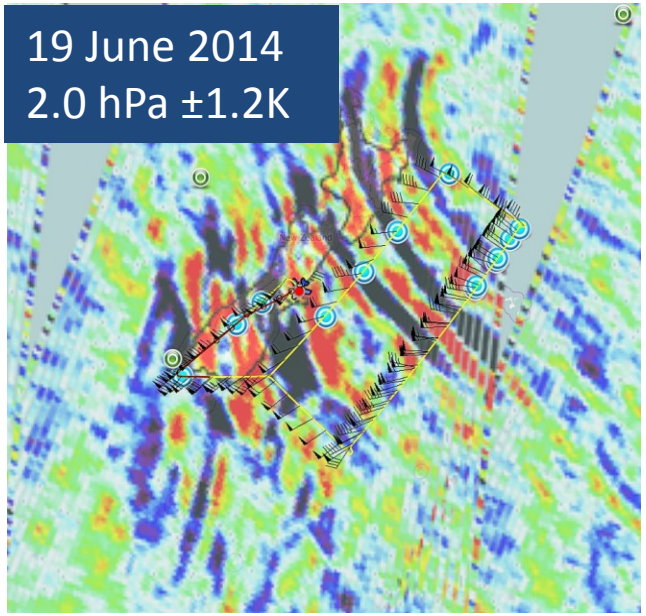


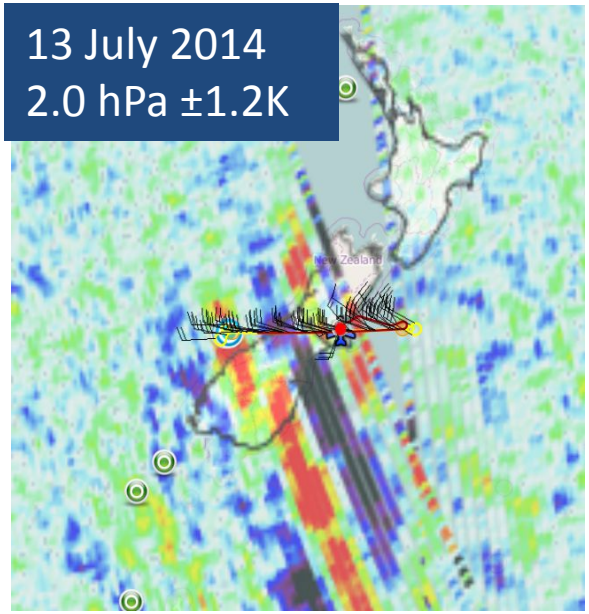
CriS



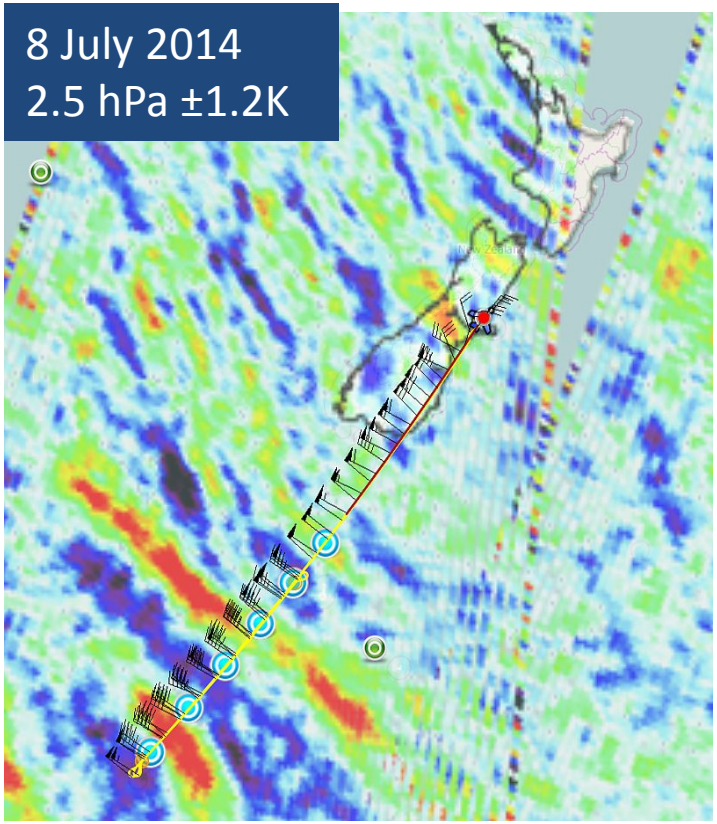
Sample AIRS-GV Coincidences: Deep Orographic Gravity Waves

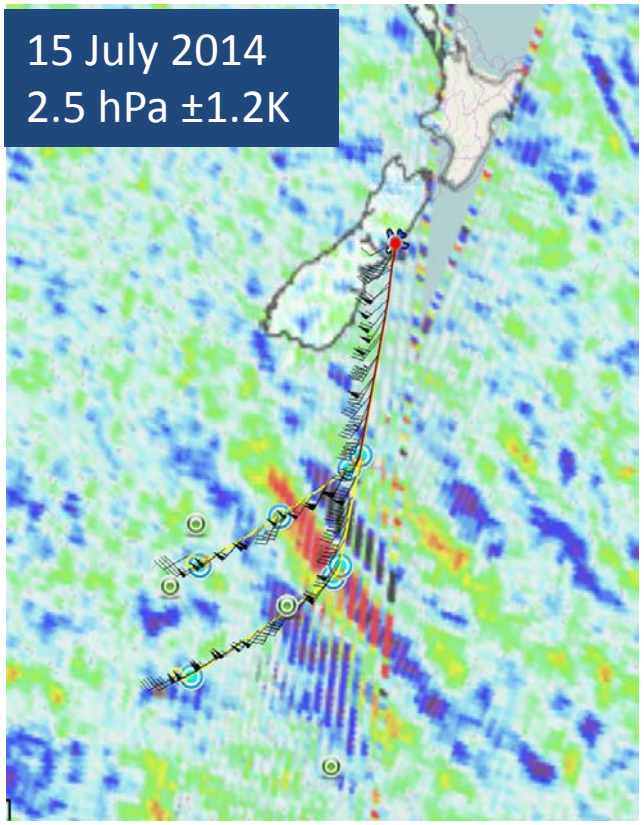


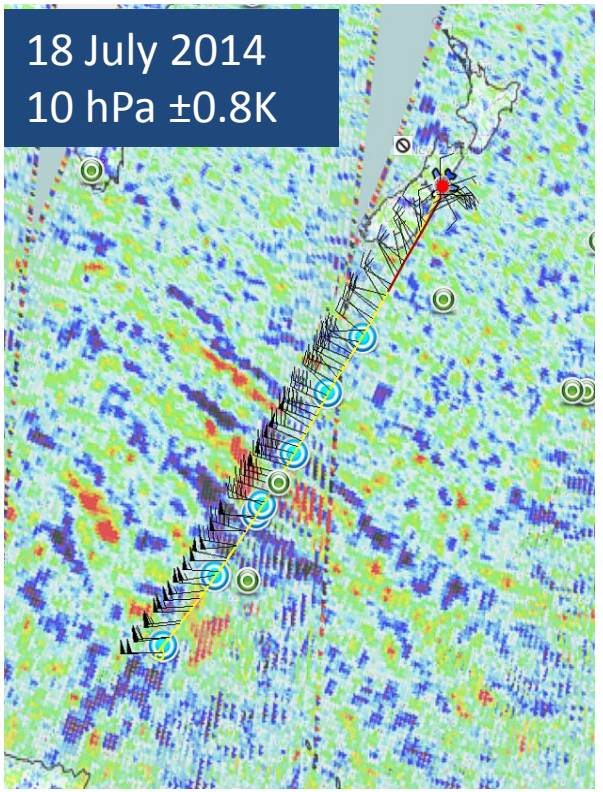




Sample AIRS-GV Coincidences: Deep Nonorographic Gravity Waves







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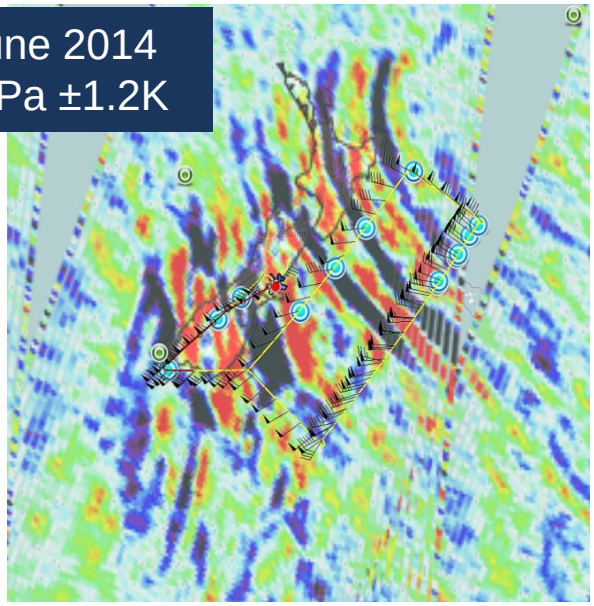
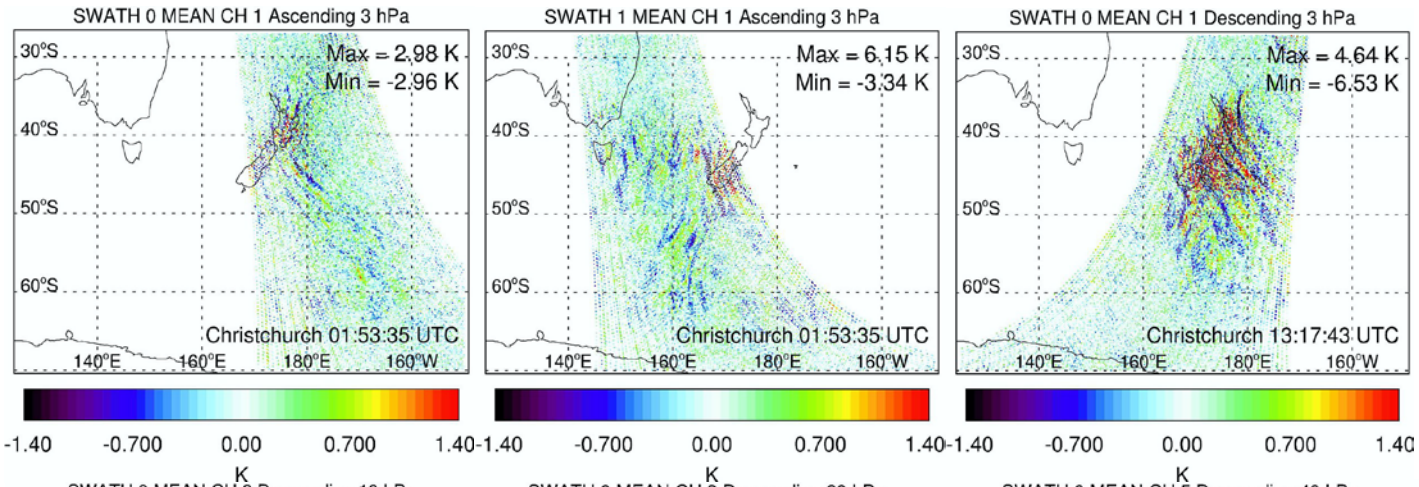
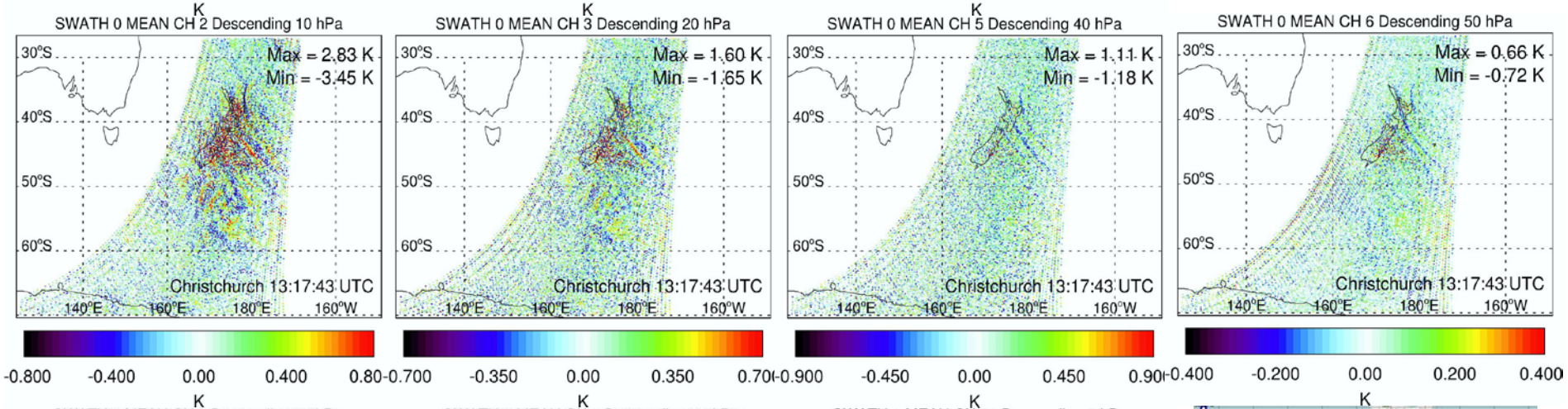
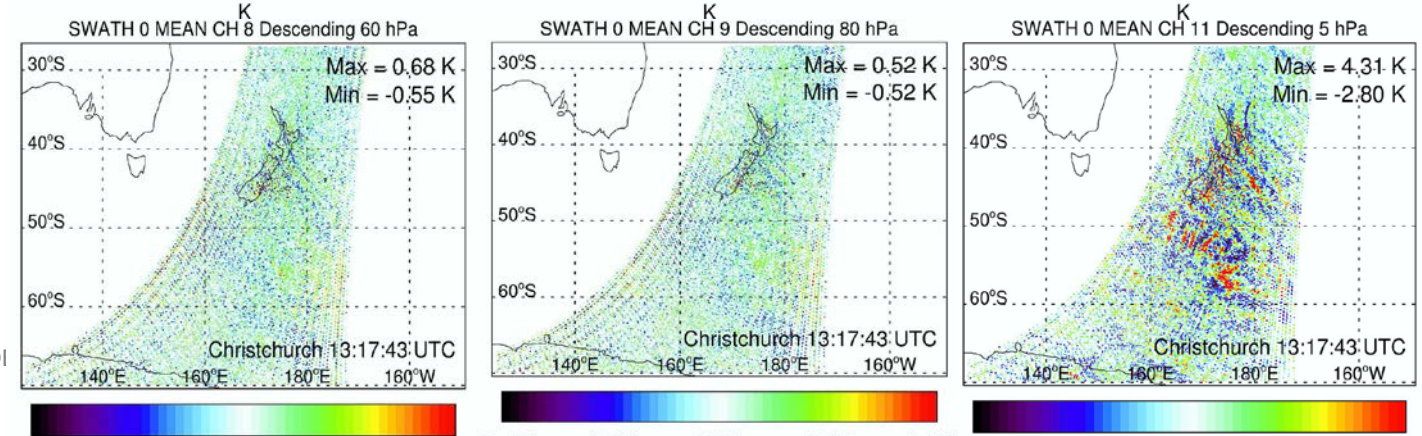
RF07: 19 June

19 June 2014
2.0 hPa ±1.2K









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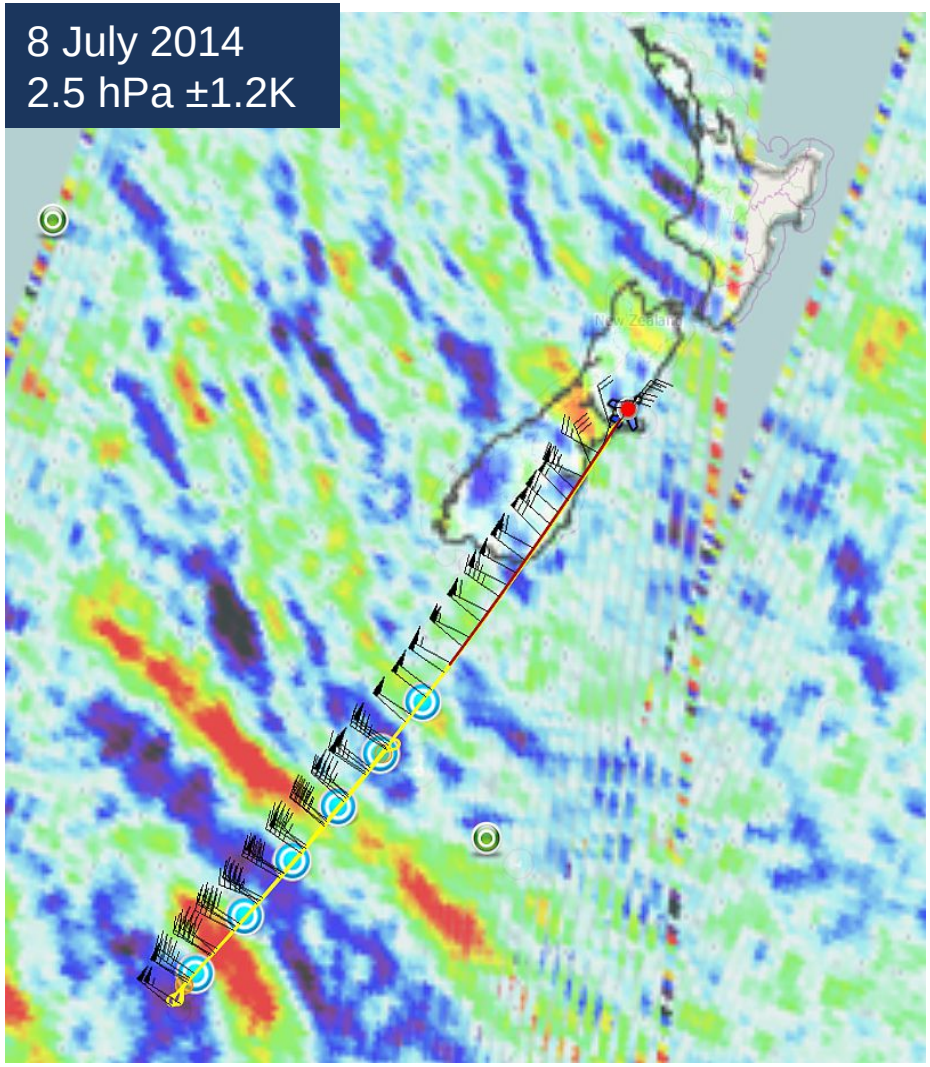
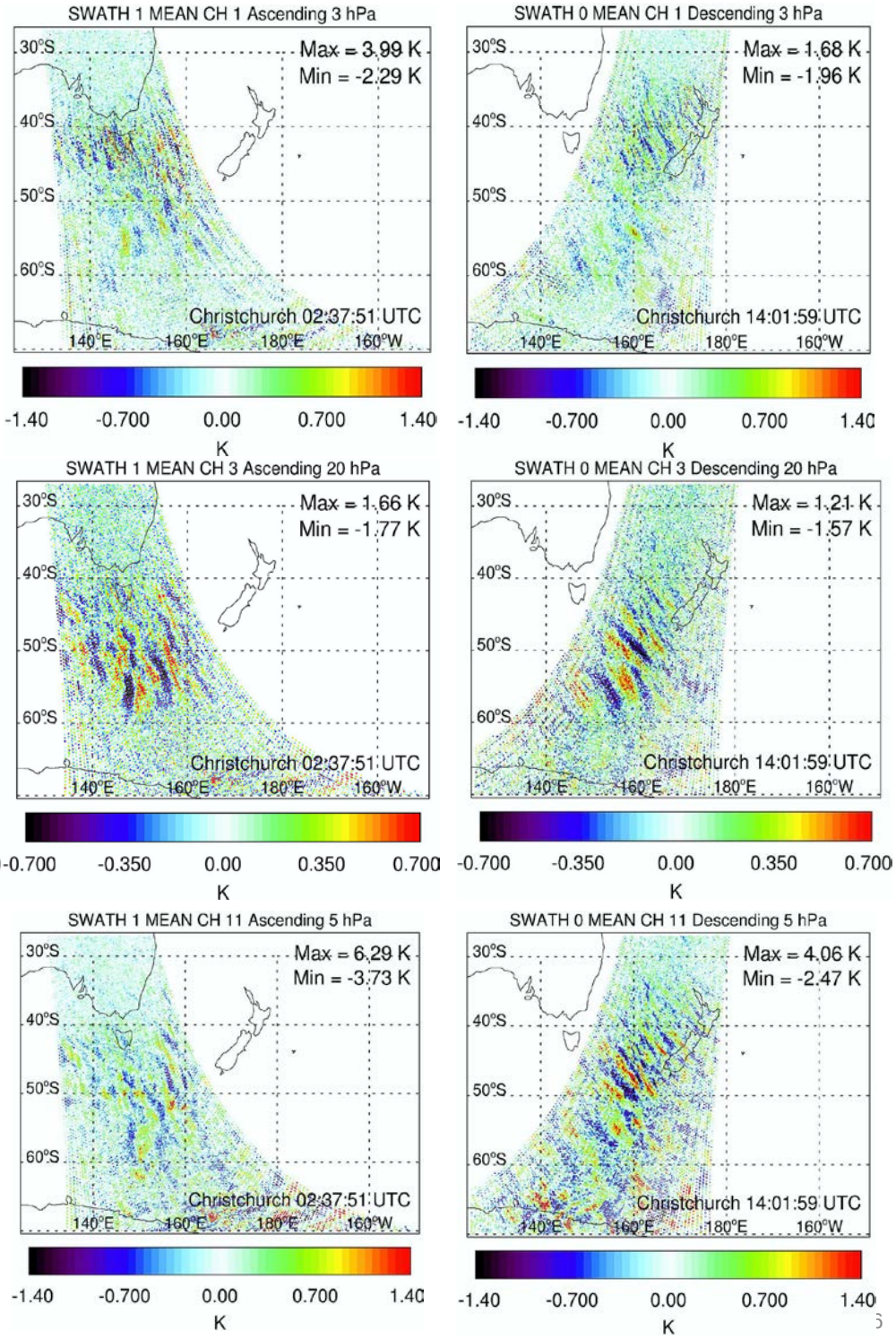
RF19: 8 July

8 July 2014
2.5 hPa ±1.2K





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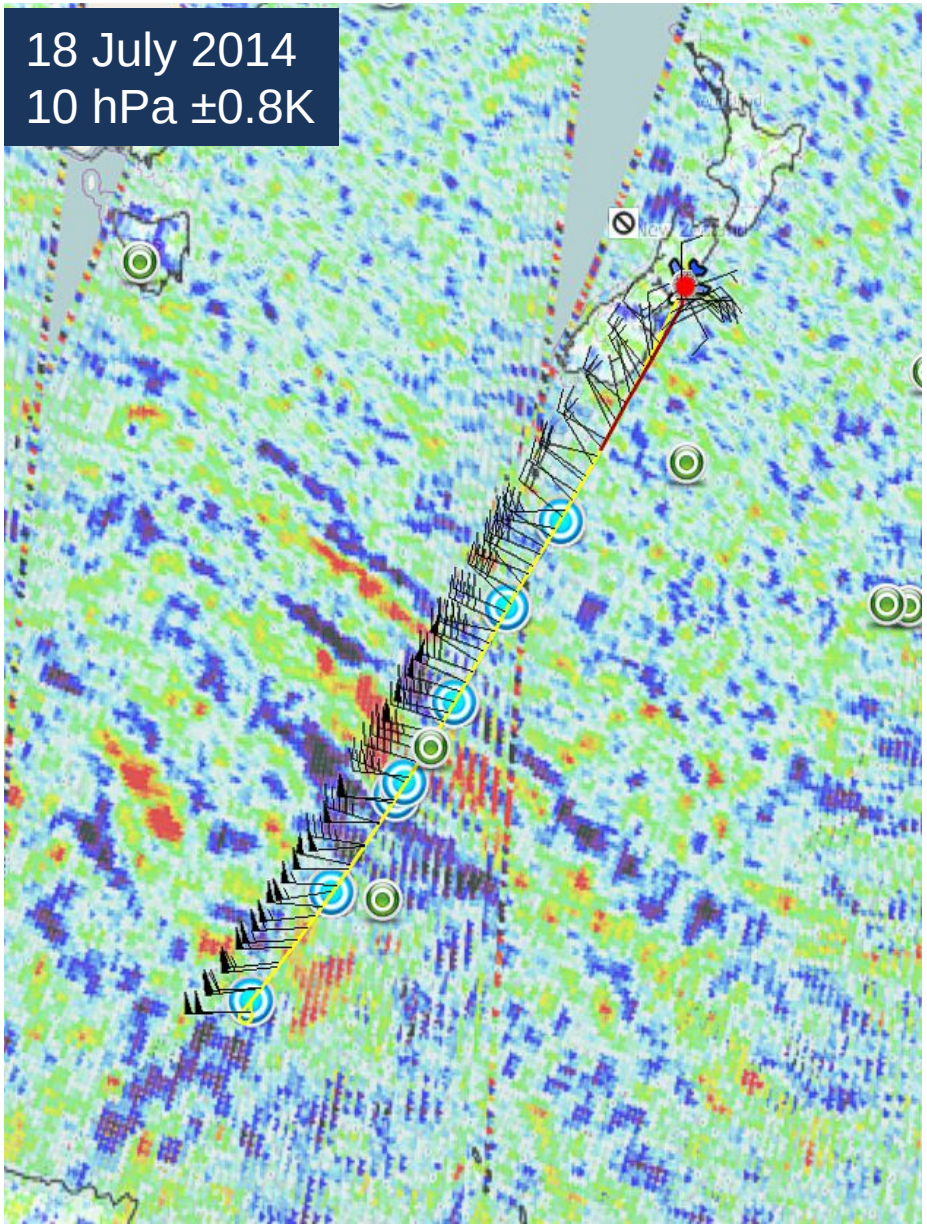
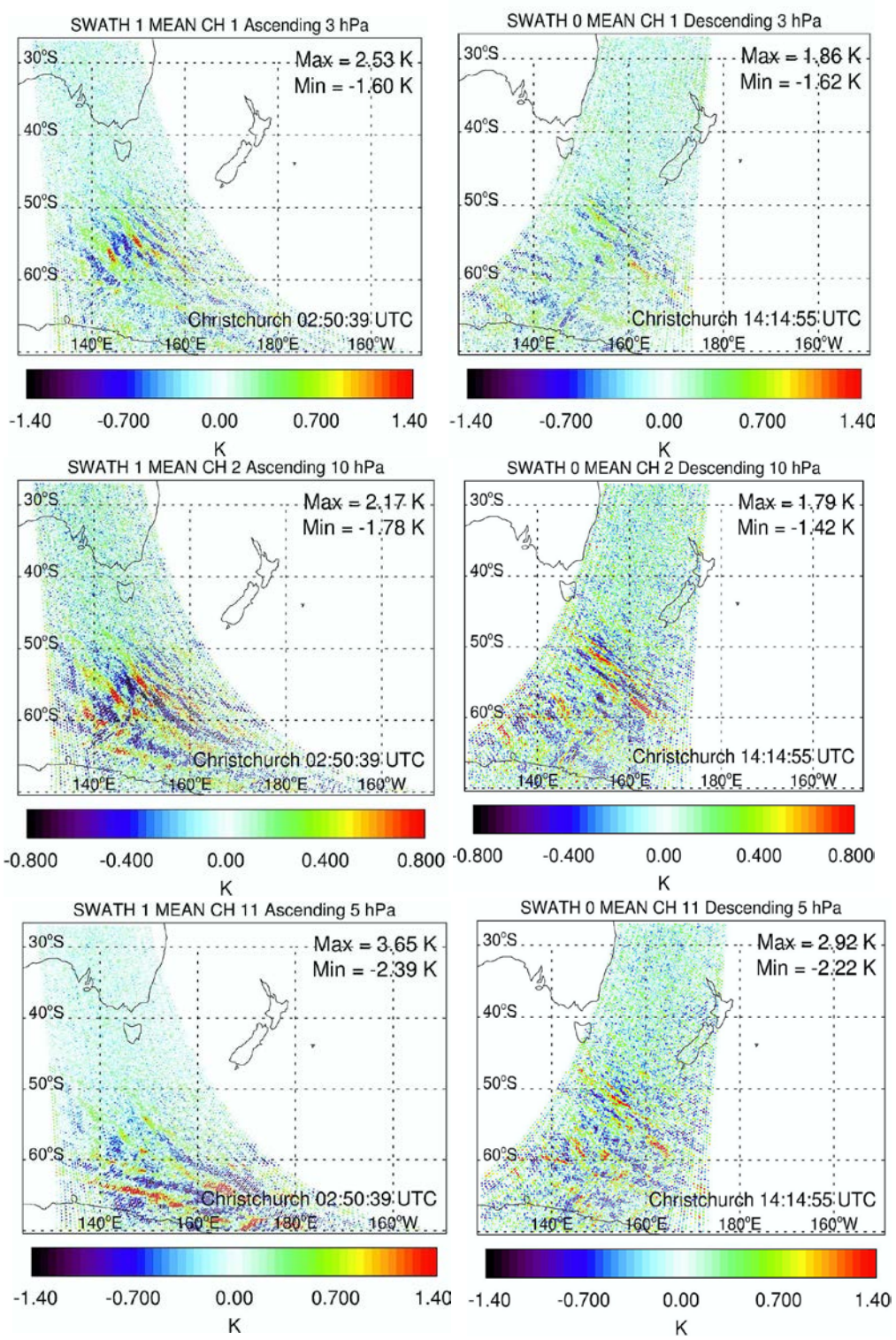
RF25: 18 July





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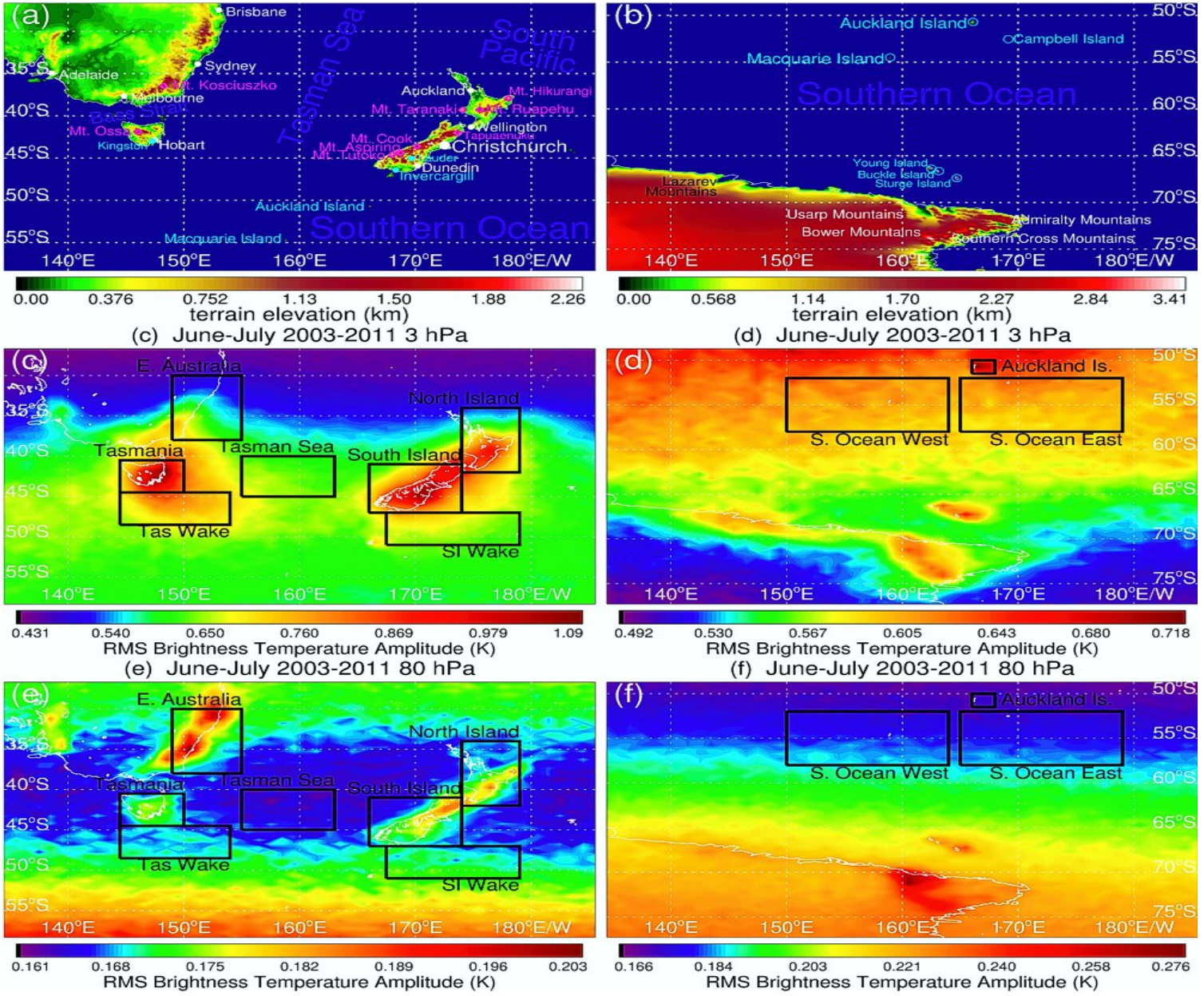
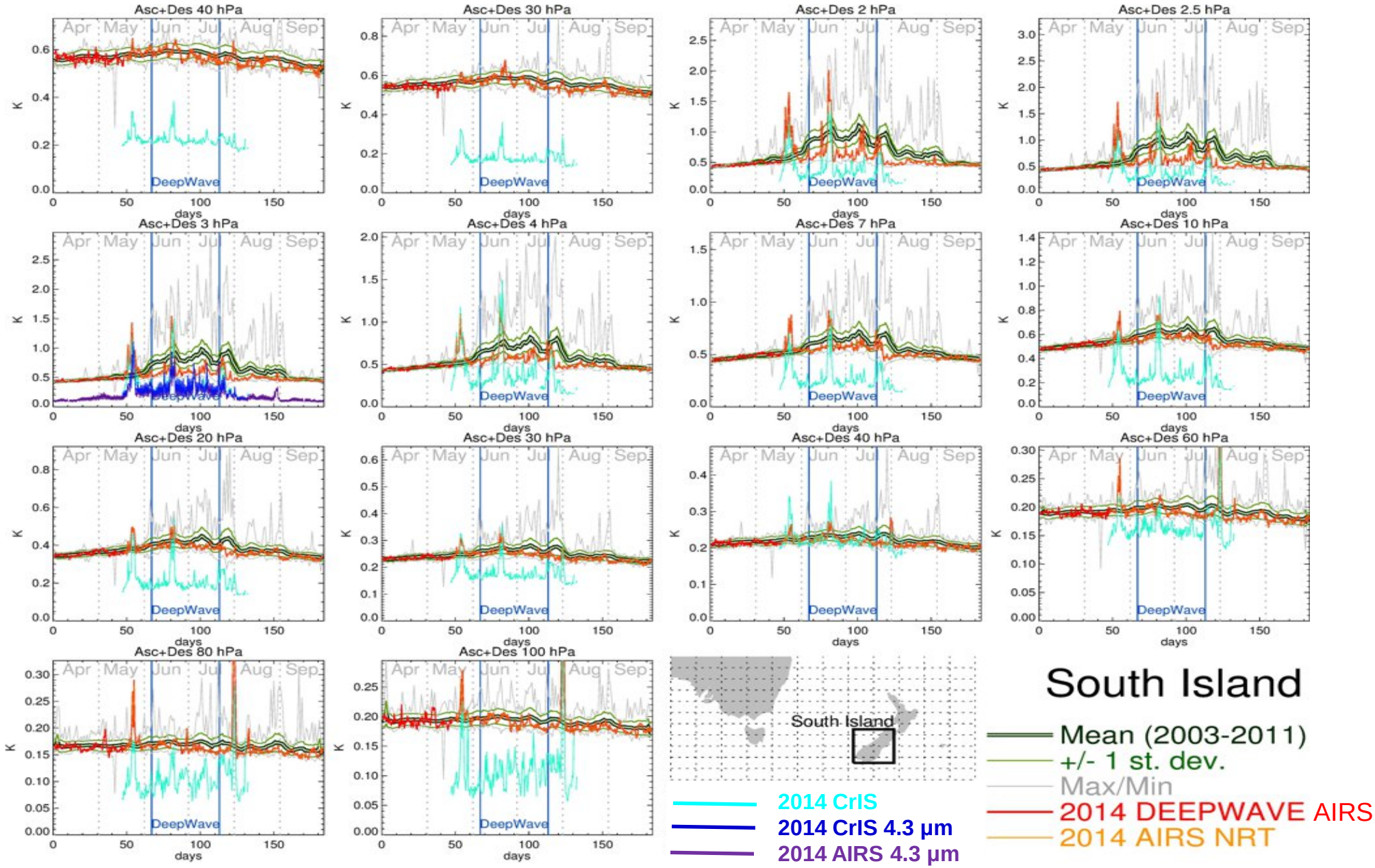
Time Series Boxes Based on Climatology



AIRS/CriS DEEPWAVE Variance Time Series: South Island



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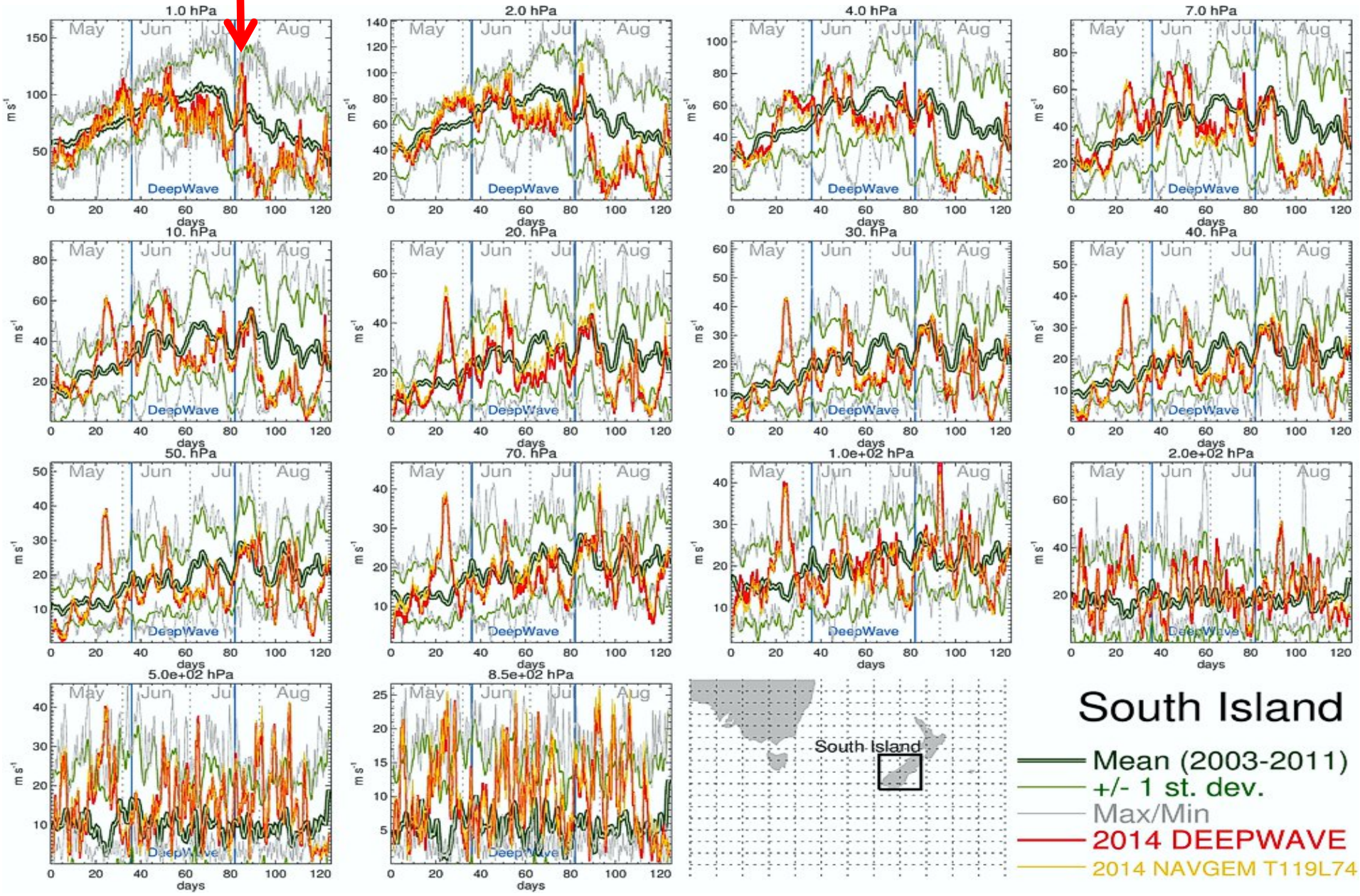
Correlation with MERRA2 Background Winds: South Island



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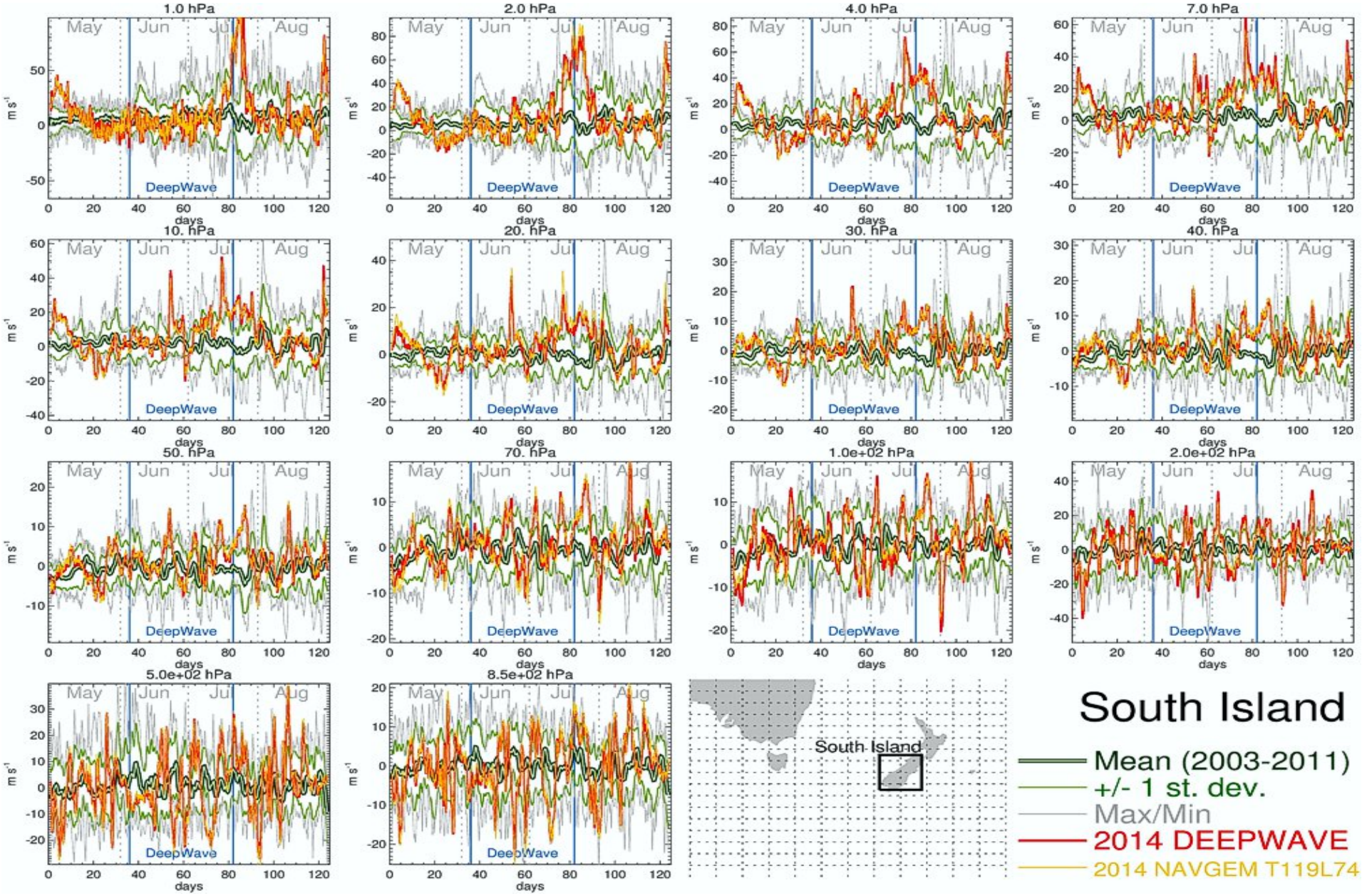
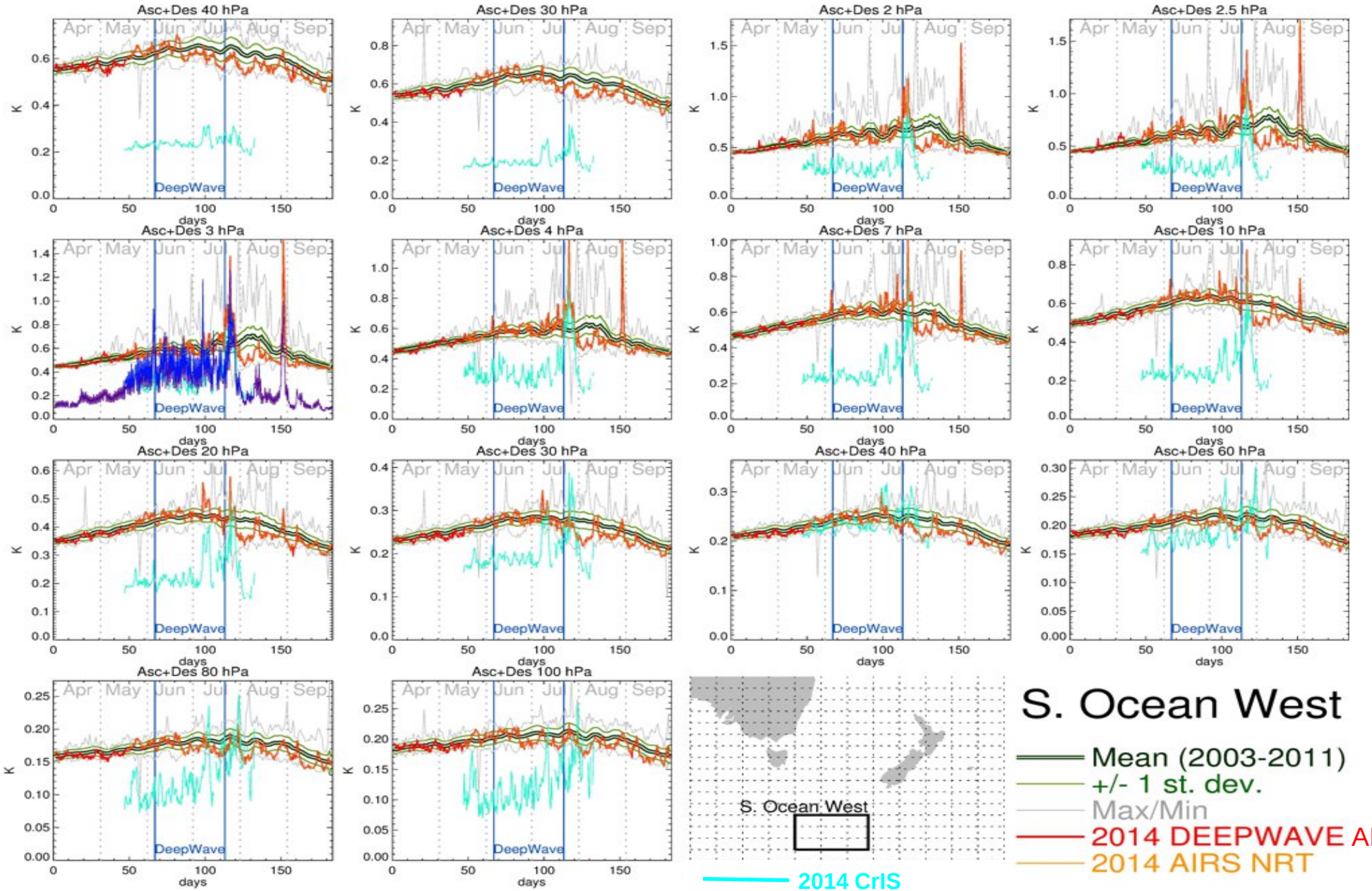
MERRA2 Meridional Wind Components: South Island



AIRS/CriS DEEPWAVE Variance Time Series: Southern Ocean West



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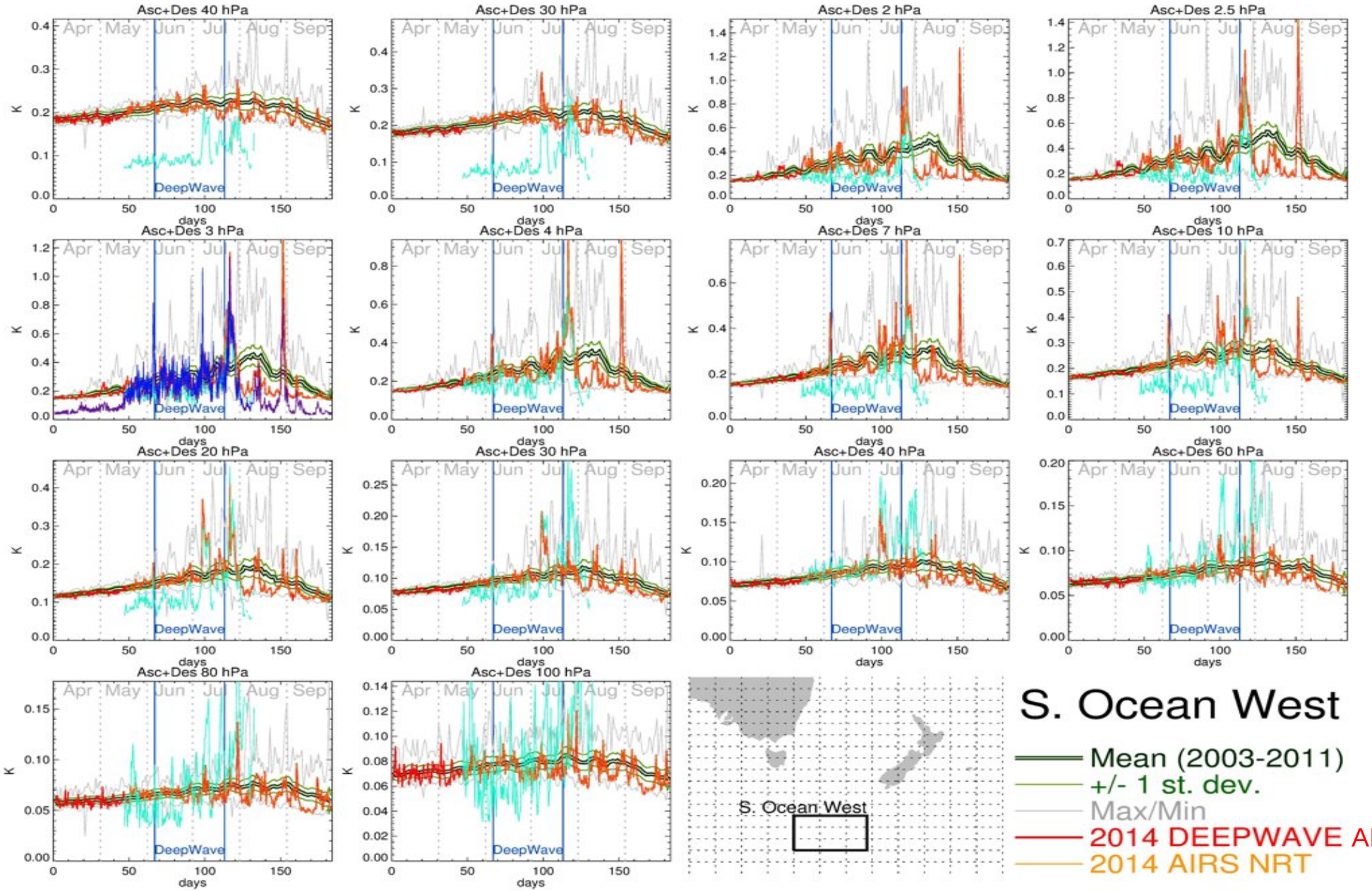
AIRS/CriS DEEPWAVE Variance Time Series: Southern Ocean West (3x3 Smoothing)



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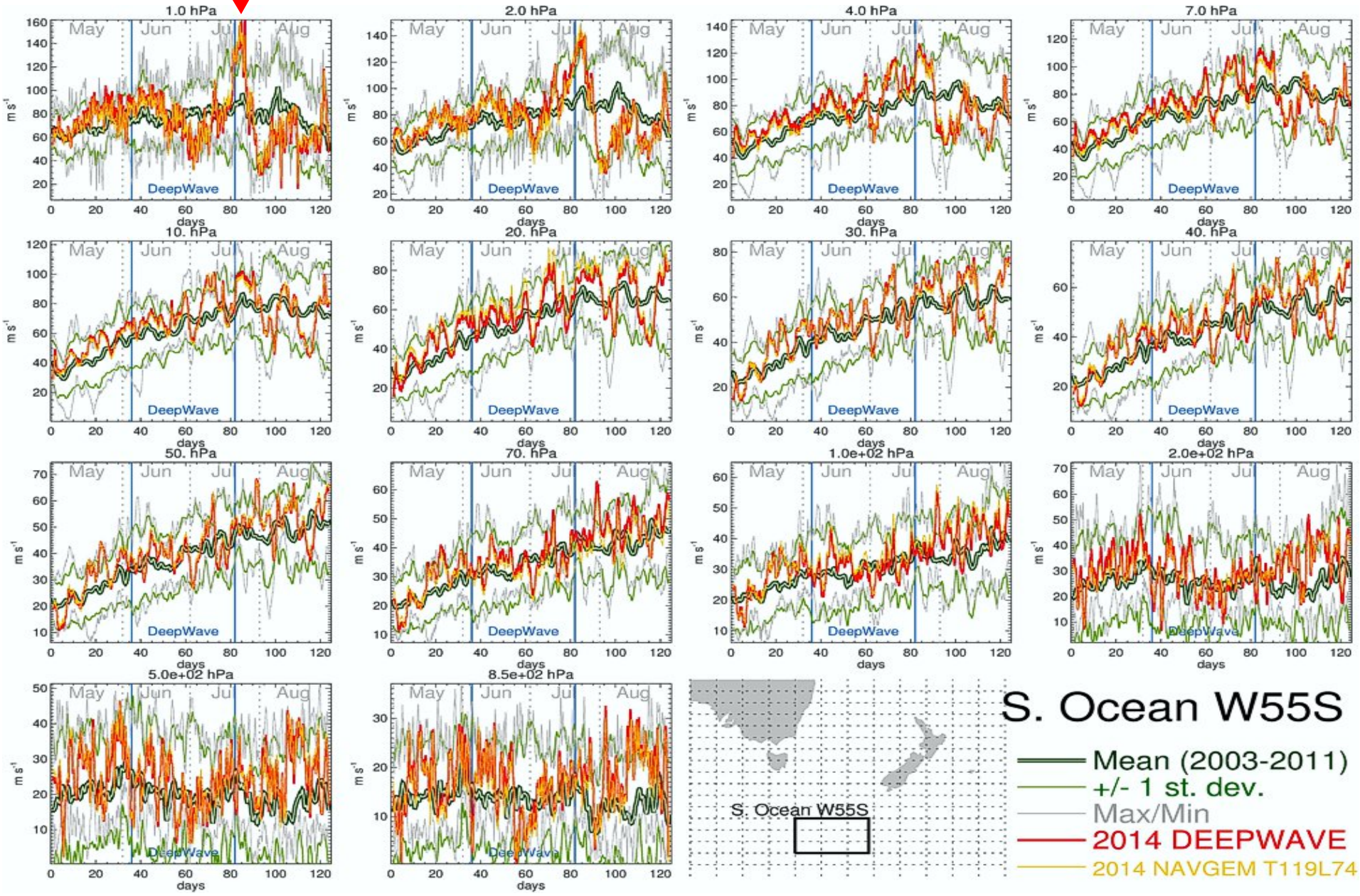
Correlation with MERRA2 Background Winds: Southern Ocean West



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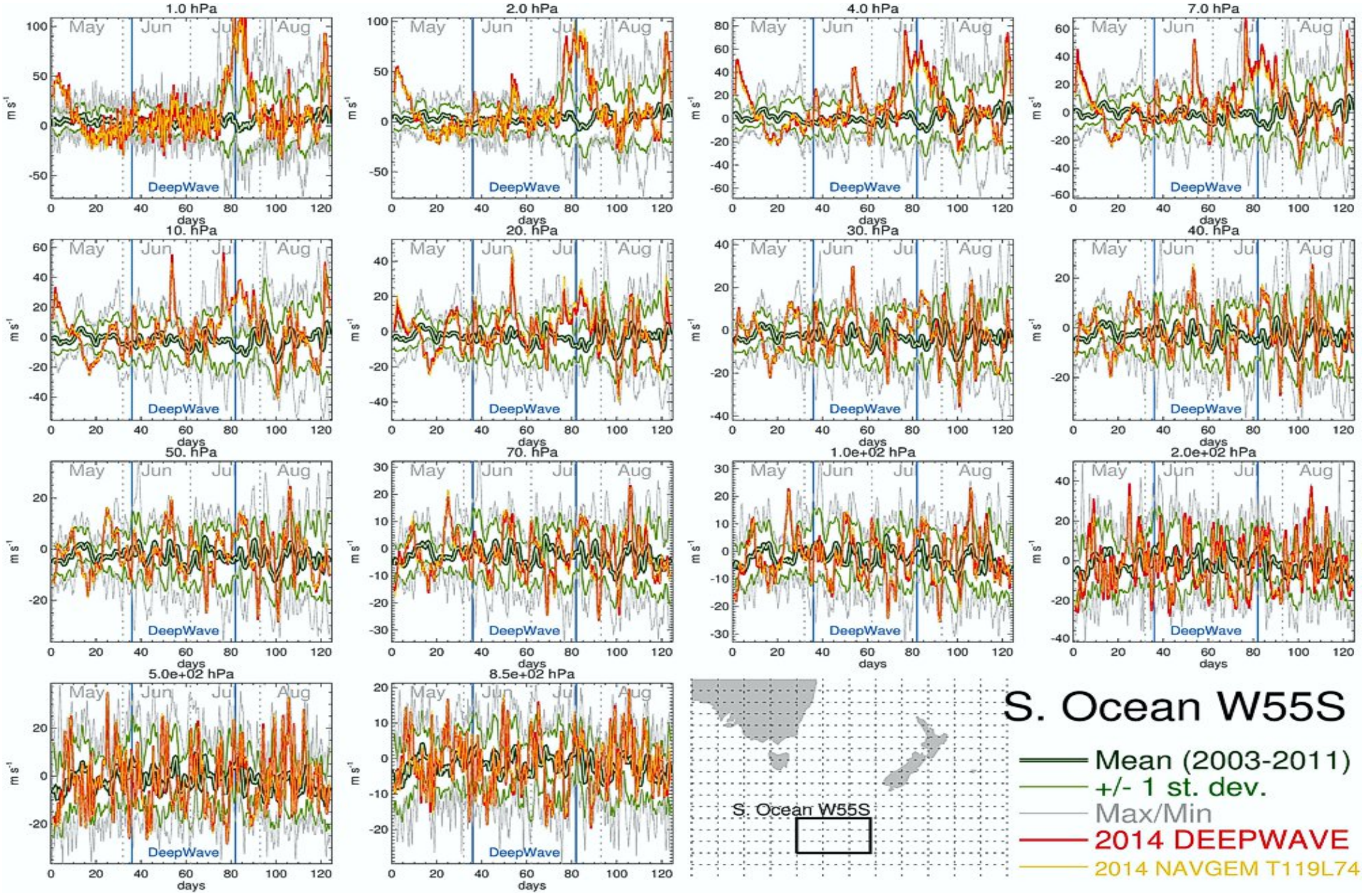
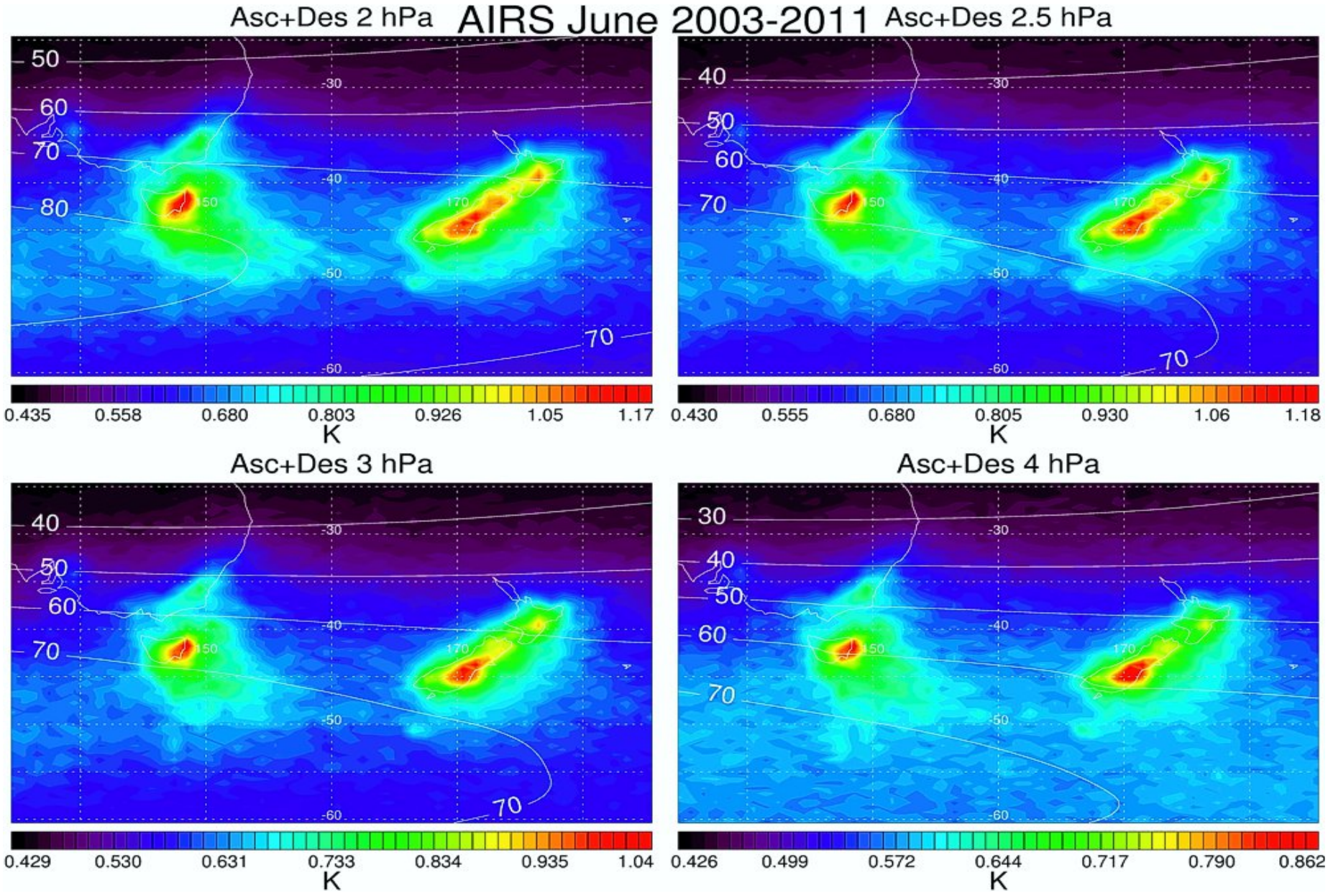
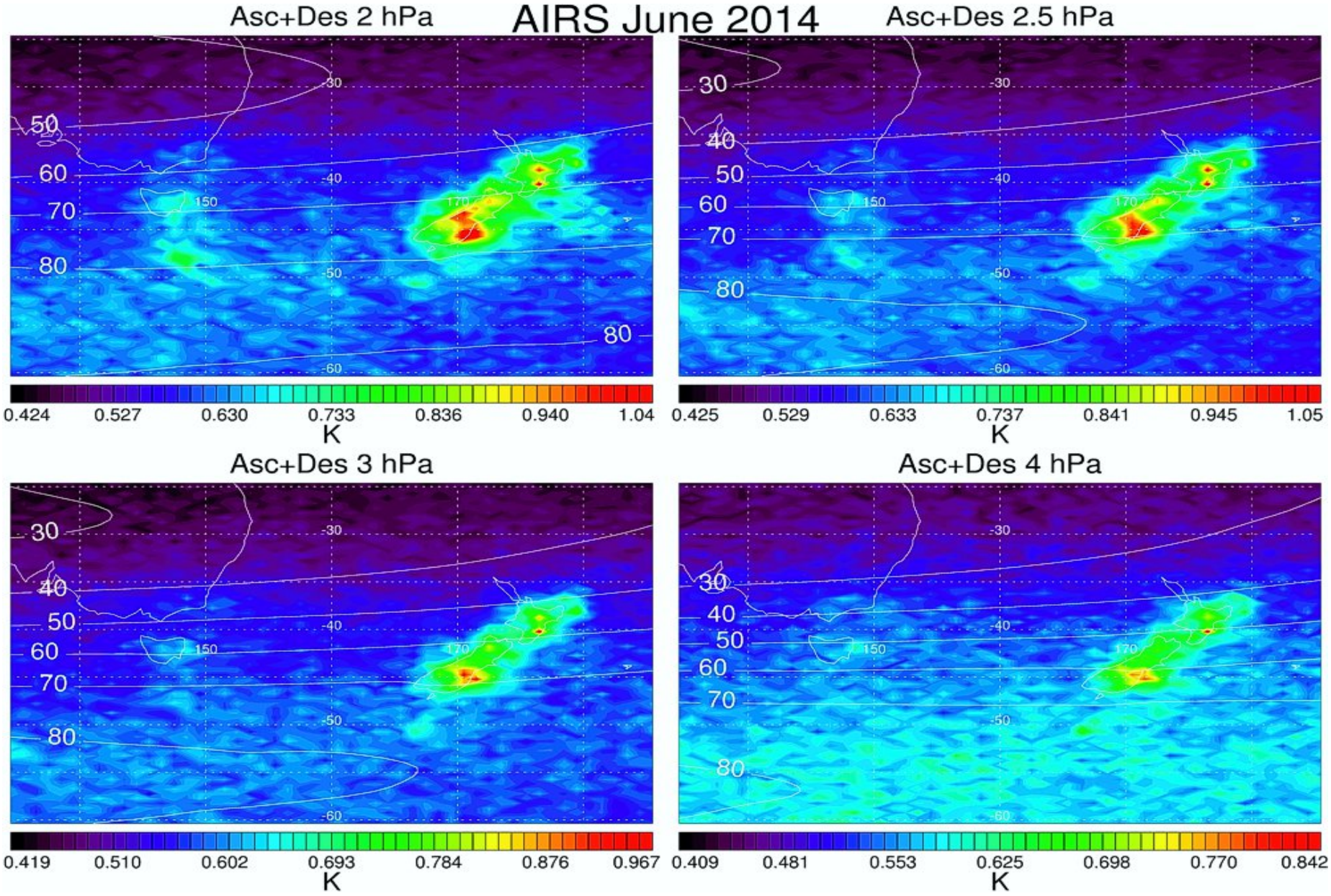
MERRA2 Meridional Wind Components: Southern Ocean West



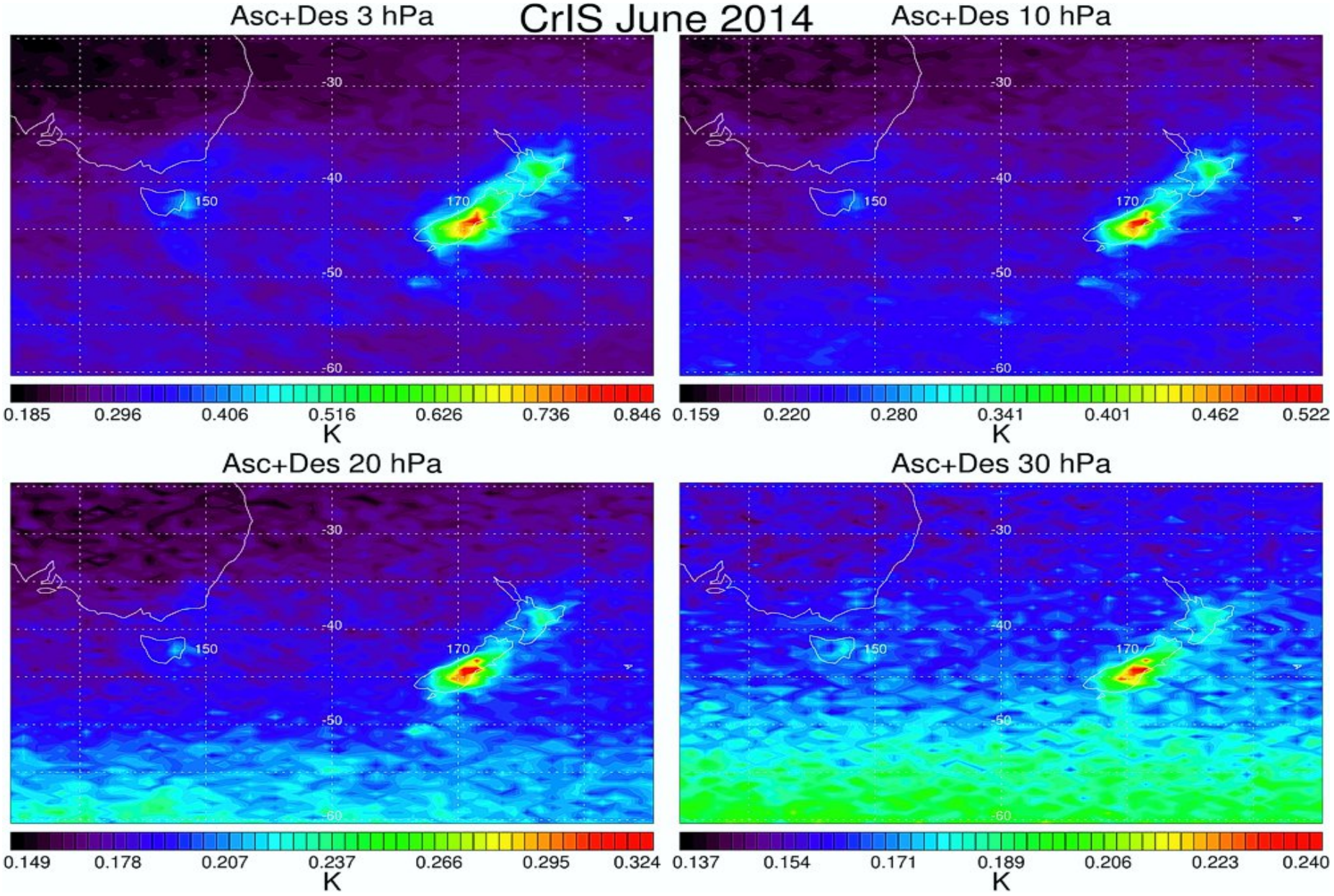
AIRS GW Variances and MERRA2 Wind Speeds": June 2003-2011



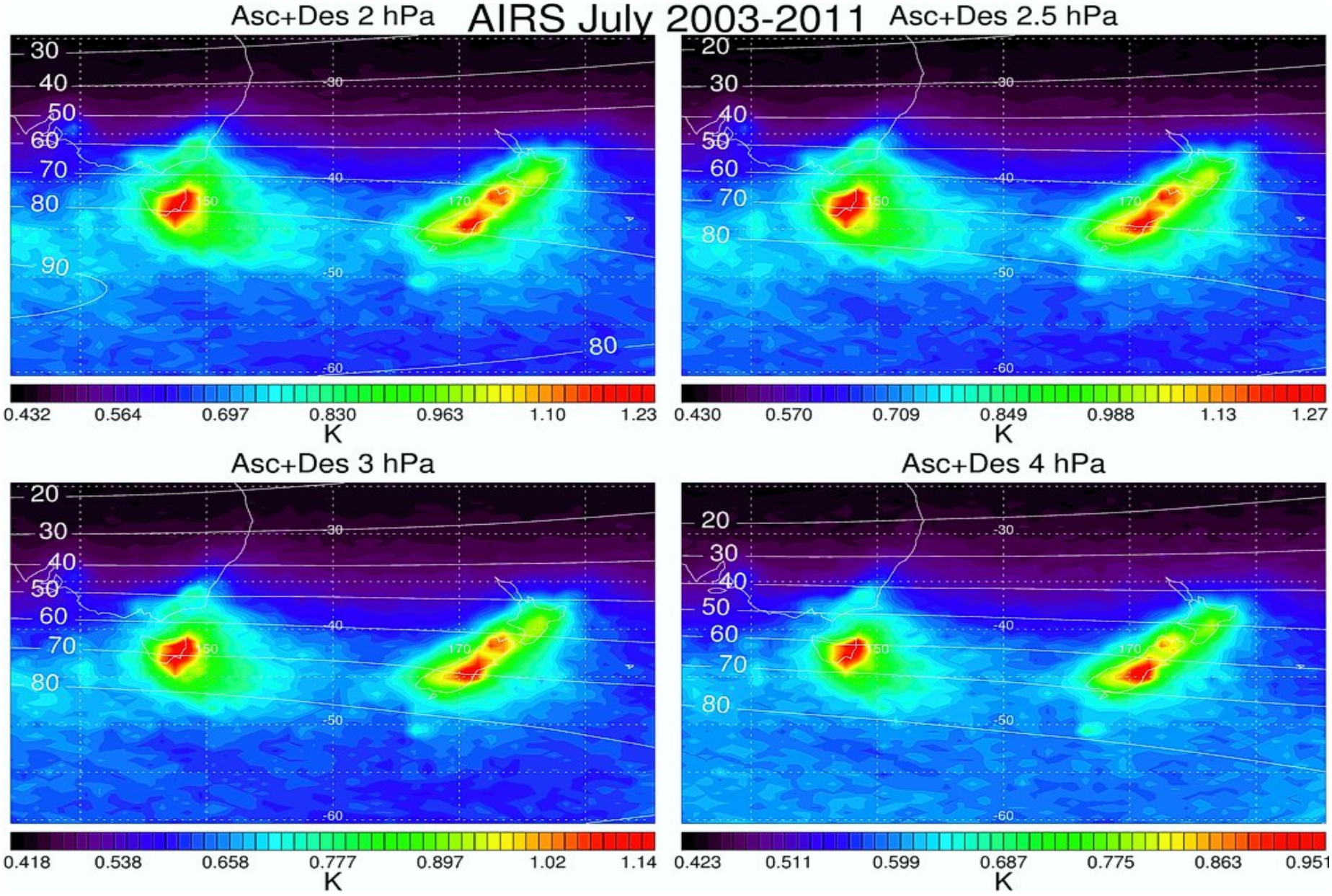
AIRS GW Variances and MERRA2 Wind Speeds": June 2014



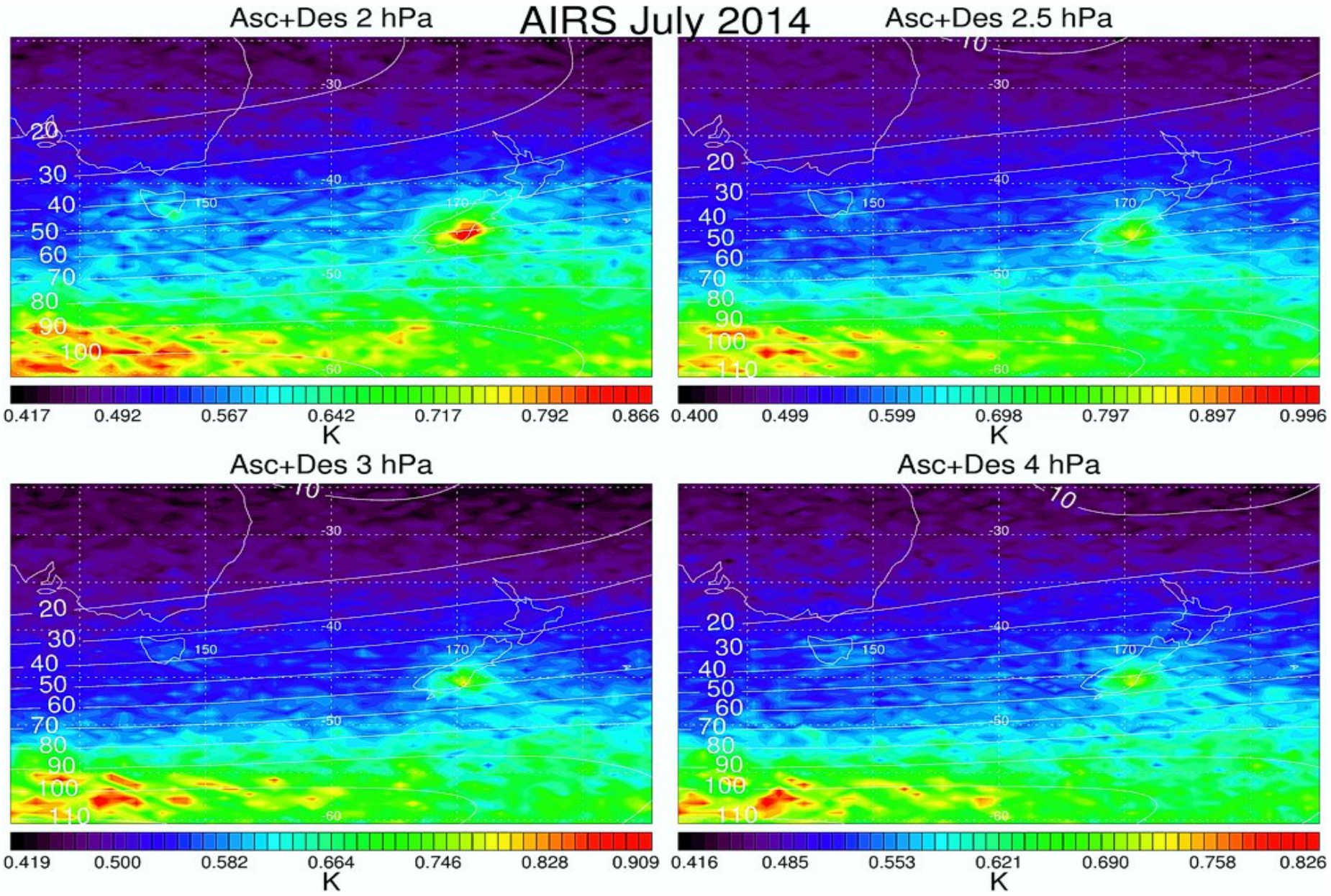
CrIS GW Variances:June 2014



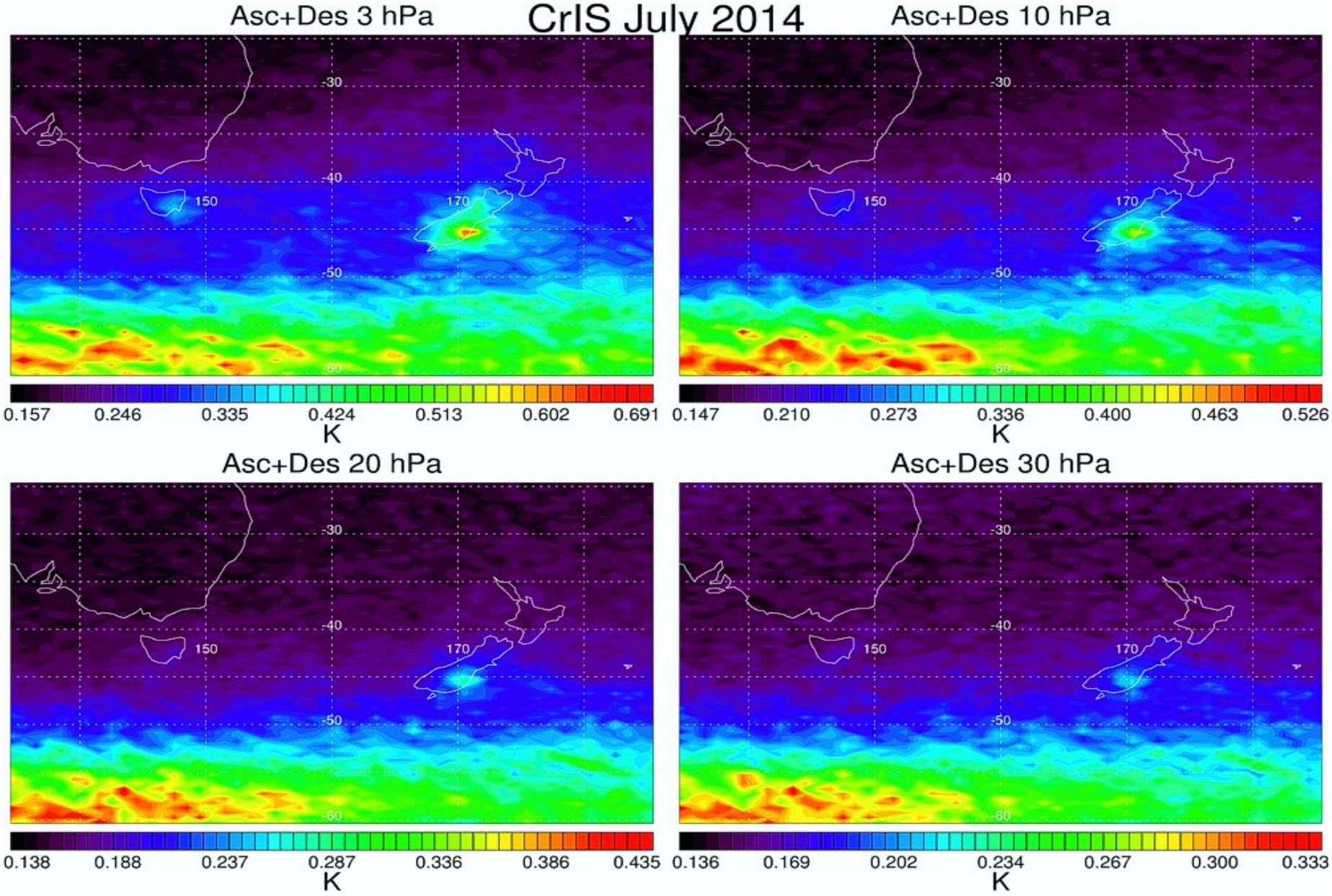
AIRS GW Variances and MERRA2 Wind Speeds": July 2003-2011



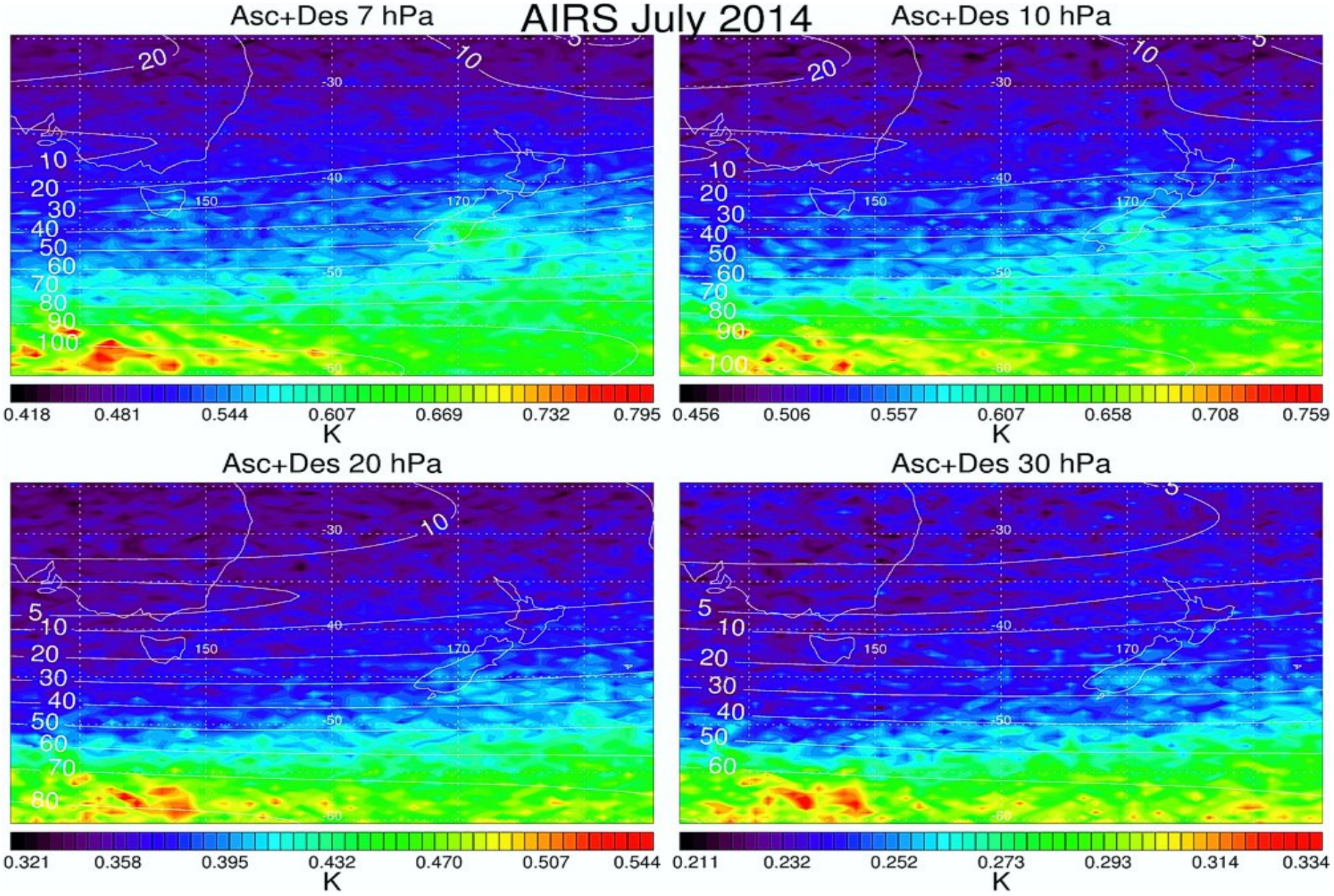
AIRS GW Variances and MERRA2 Wind Speeds": July 2014



CrIS GW Variances: July 2014



AIRS GW Variances and MERRA2 Wind Speeds" 7-30 hPa: July 2014



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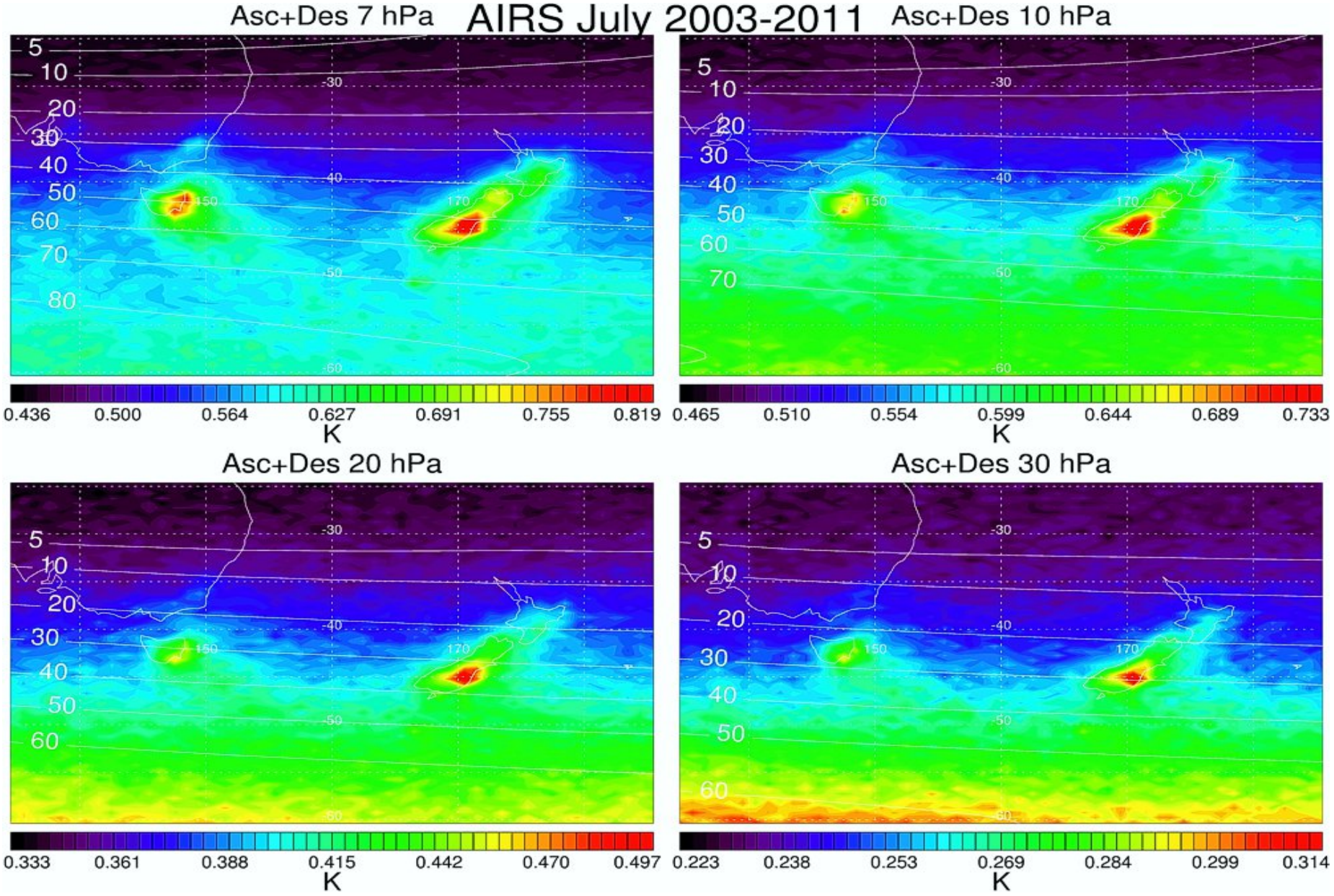
AIRS GW Variances and MERRA2 Wind Speeds" 7-30 hPa: July 2003-2011



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Progress Report on Following Topics

NAVGEM Reanalysis for 2014 DEEPWAVE Austral Winter

Stratospheric Gravity Waves in AIRS and CrIS 15μm and 4.3 μm Radiances

Deep Gravity-Wave Dynamics over the Auckland Islands and Macquarie Island during RF23

- See my AGU talk next Wednesday
- Eckermann et al. (2016), Dynamics of orographic gravity waves observed in the mesosphere over the Auckland Islands during the Deep Propagating Gravity Wave Experiment (DEEPWAVE), J. Atmos. Sci., 73, 3855-3876, doi:10.1175/JAS-D-16-0059.1.
- Broutman et al. (2017), A stationary phase solution for mountain waves with application to mesospheric mountain waves generated by Auckland Island, J. Geophys. Res., revised.

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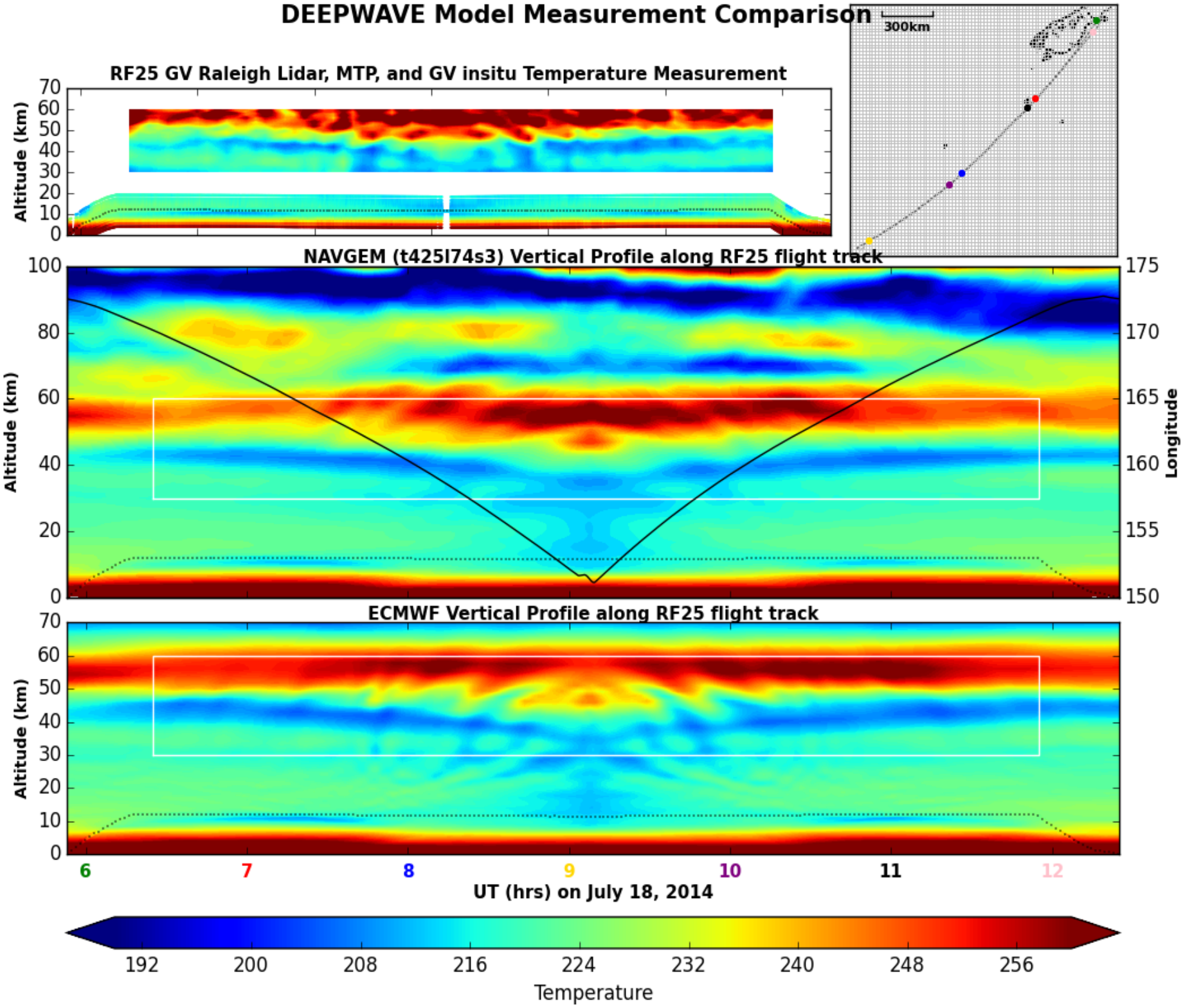
Backup Slides


DEEPWAVE Model Measurement Comparison
RF25 GV Raleigh Lidar, MTP, and GV insitu Temperature Measurement
Altitude (km)
300km
NAVGEM (t425l74s3) Vertical Profile along RF25 flight track
Altitude (km)
Longitude
ECMWF Vertical Profile along RF25 flight track
Altitude (km)
6
7
8
9
10
11
12
UT (hrs) on July 18, 2014
192
200
208
216
224
232
240
248
256
Temperature

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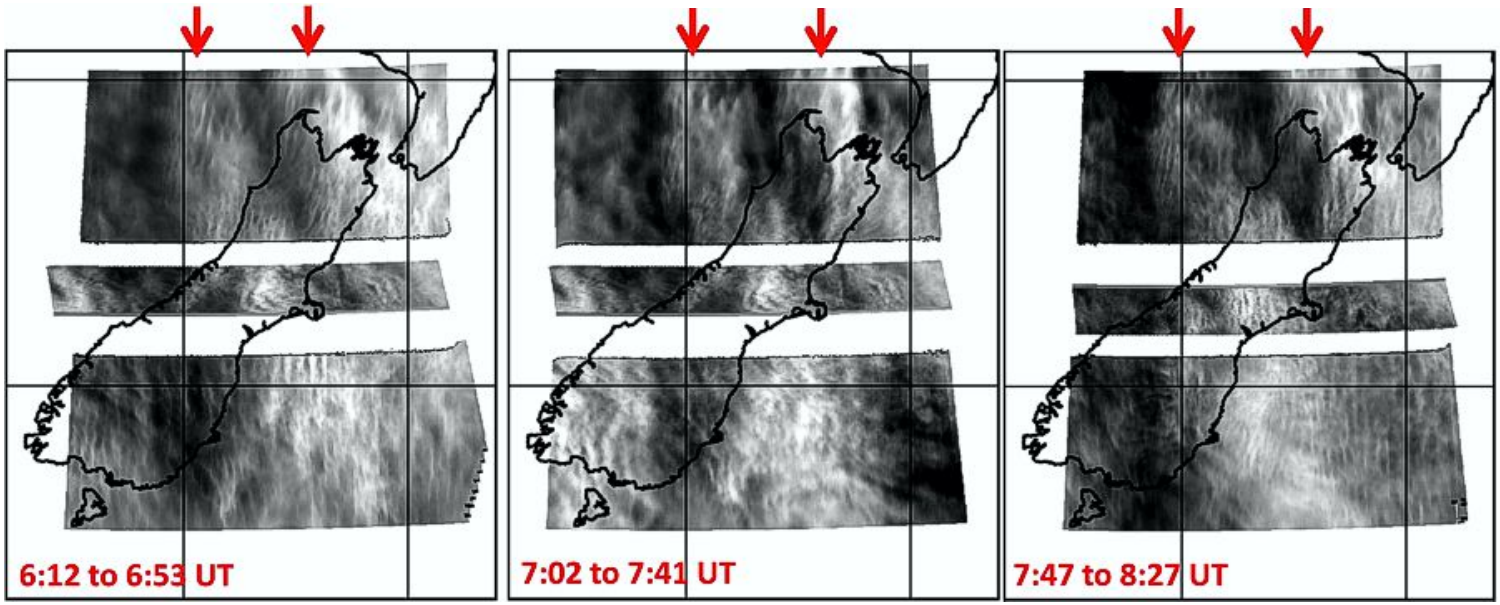
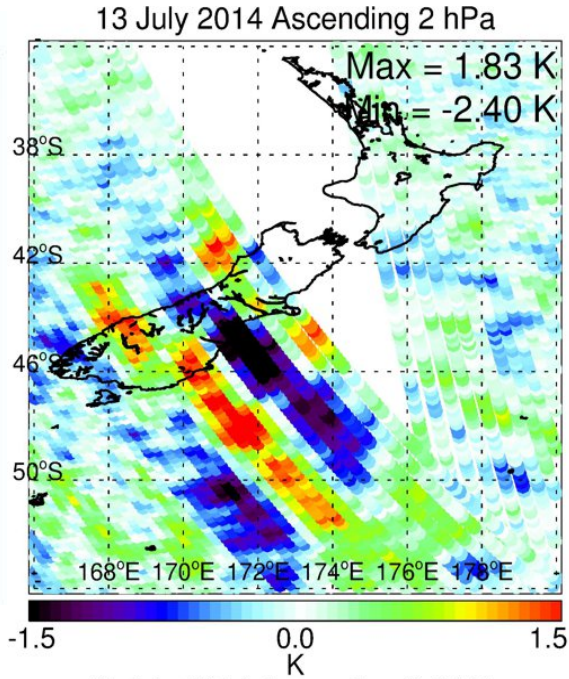
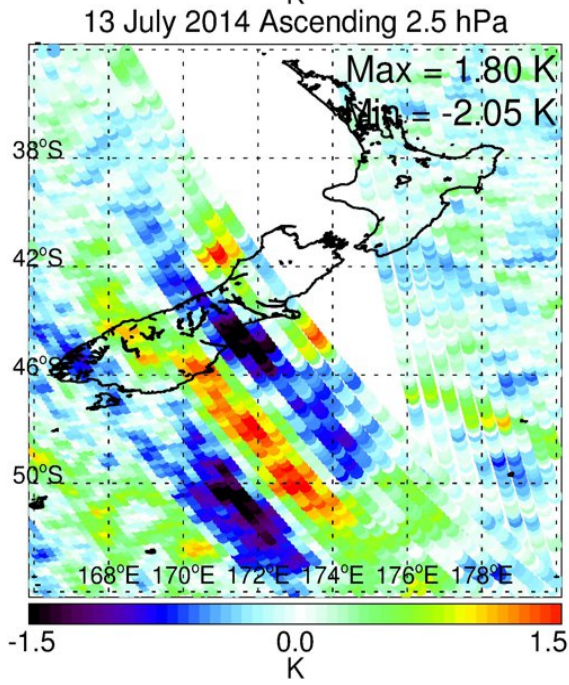
DEEPWAVE RF22
Origin of Observed GW Phase Orientation





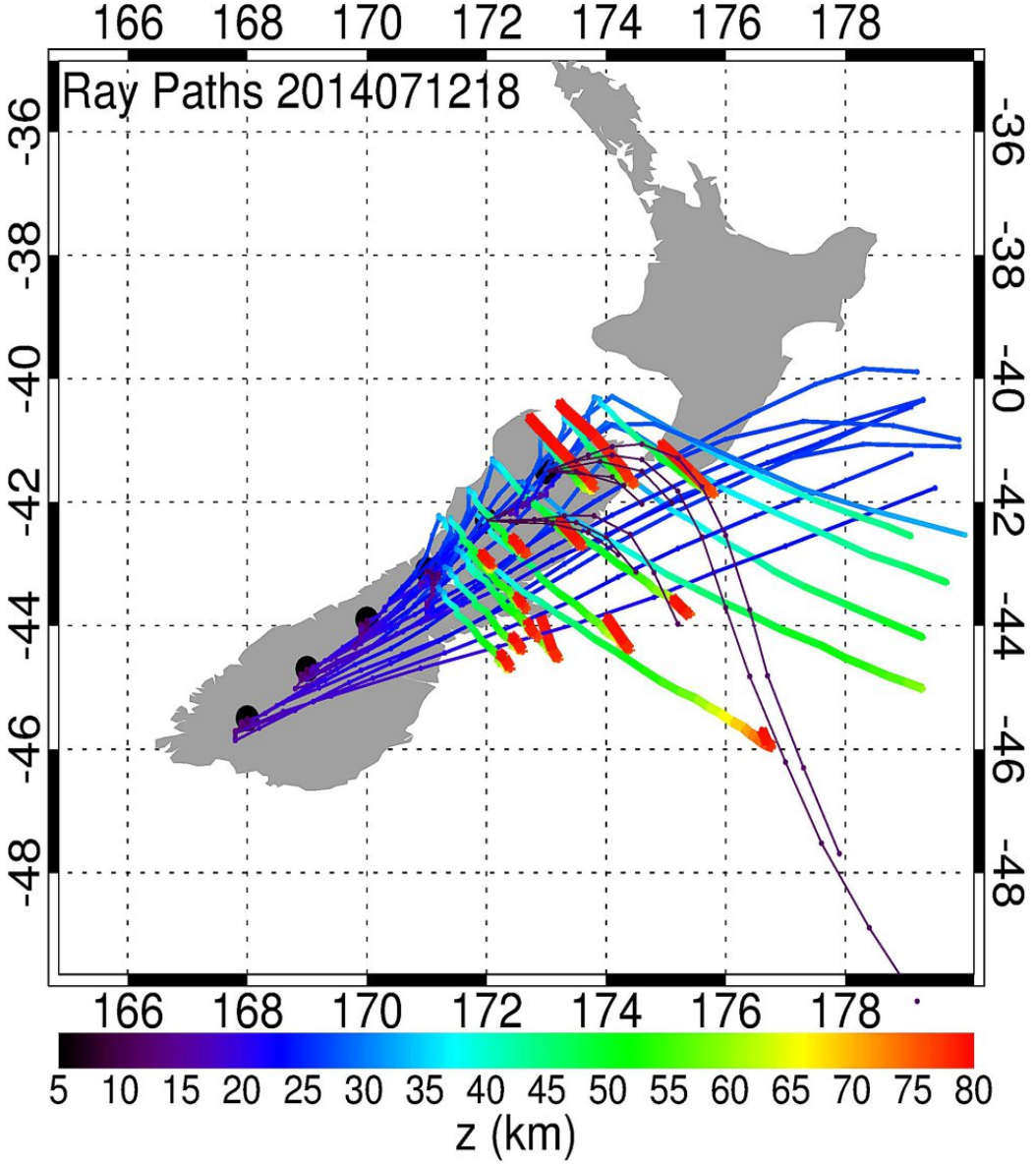


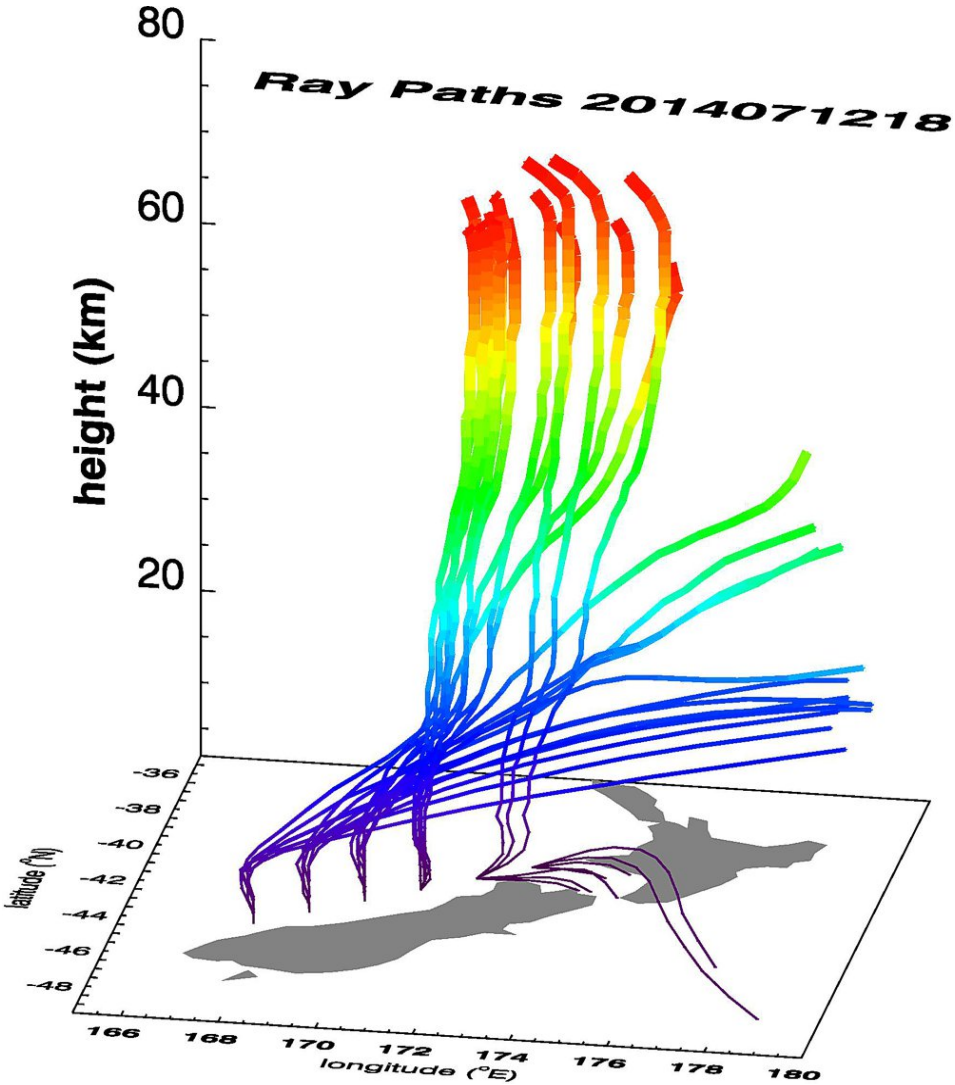
Very large amplitude waves (λ_h~200-300 km) observed in the upper stratosphere and MLT over the South Island **with odd phase orientation**

Preceded by strong surface forcing previous night and early in day (sampled by DLR Falcon), which abated at flight time

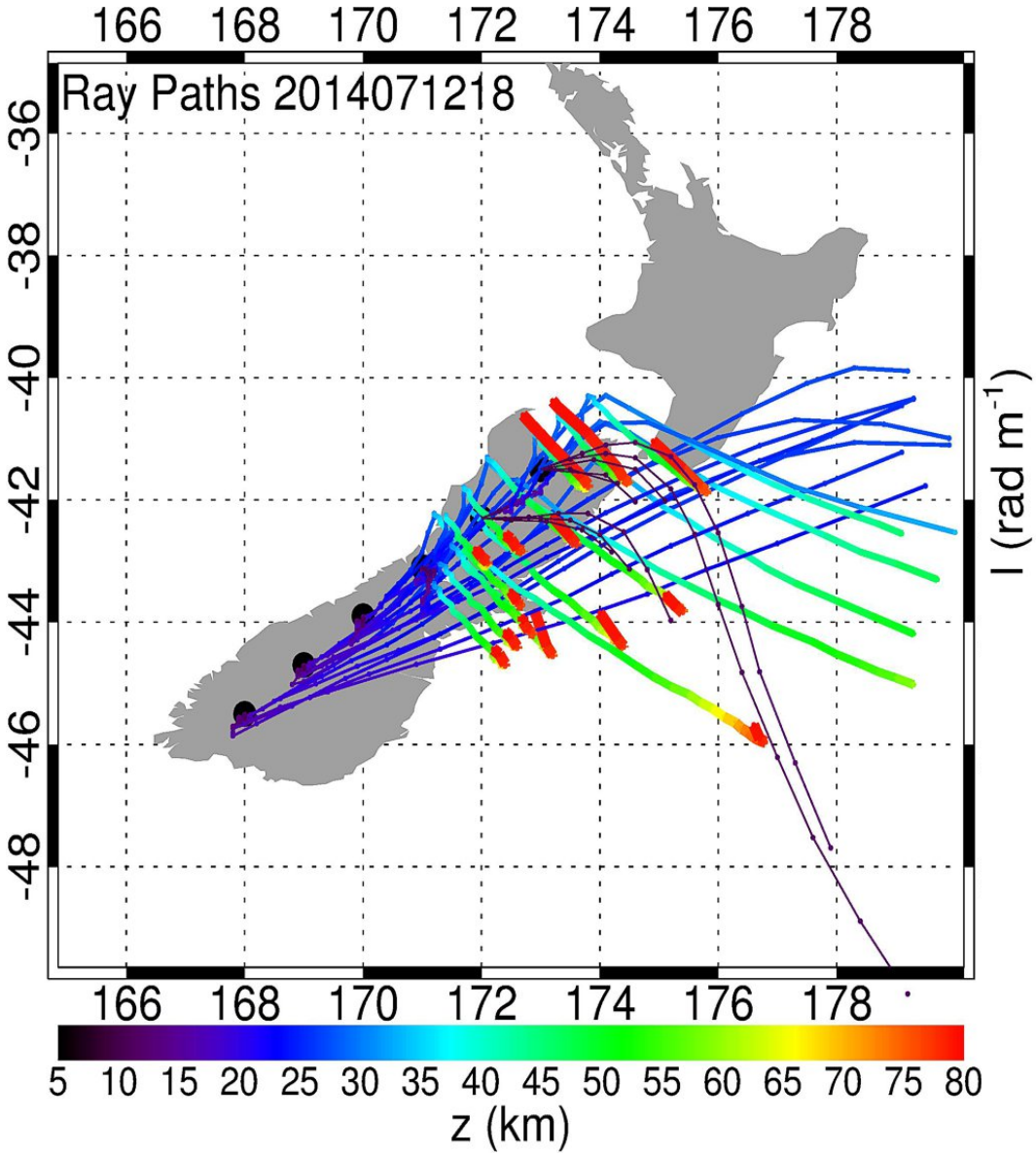
Anomalously strong stratopause jet at the time

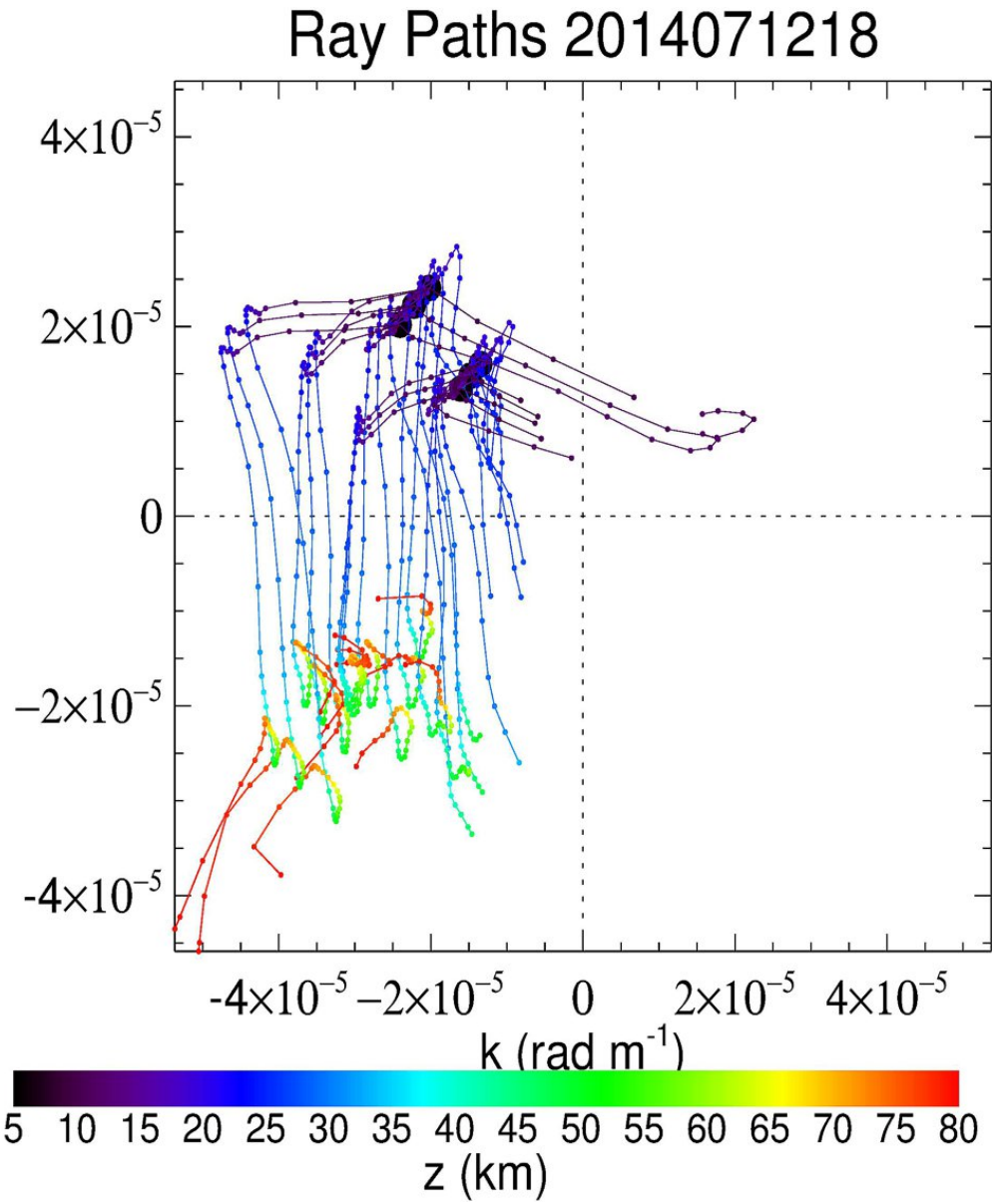
Orographic Gravity Wave Ray Paths Using NAVGEM Backgrounds: 12 July 1800 UTC





Orographic Gravity Wave Ray Paths Using NAVGEM Backgrounds: 12 July 1800 UTC





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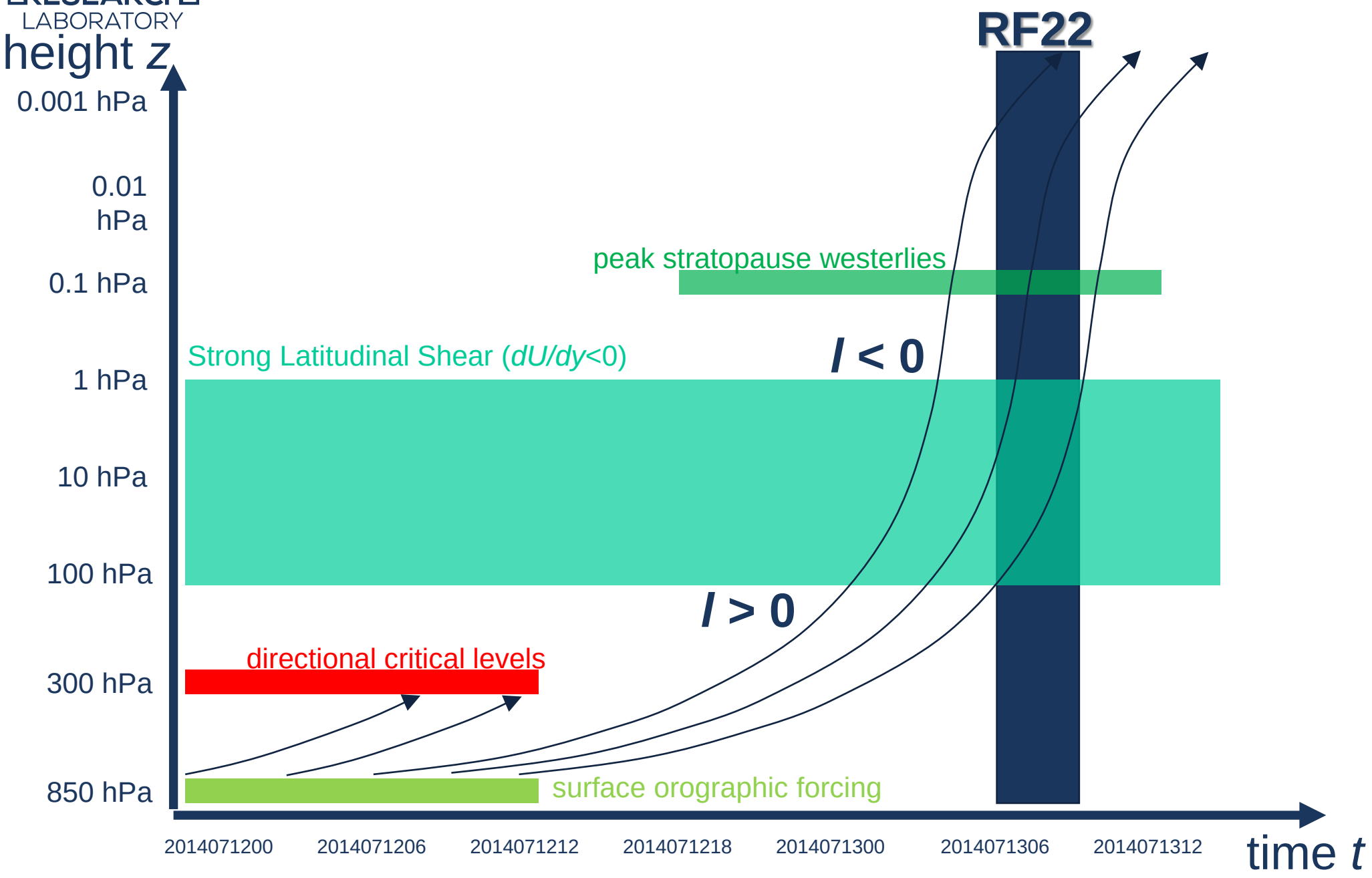
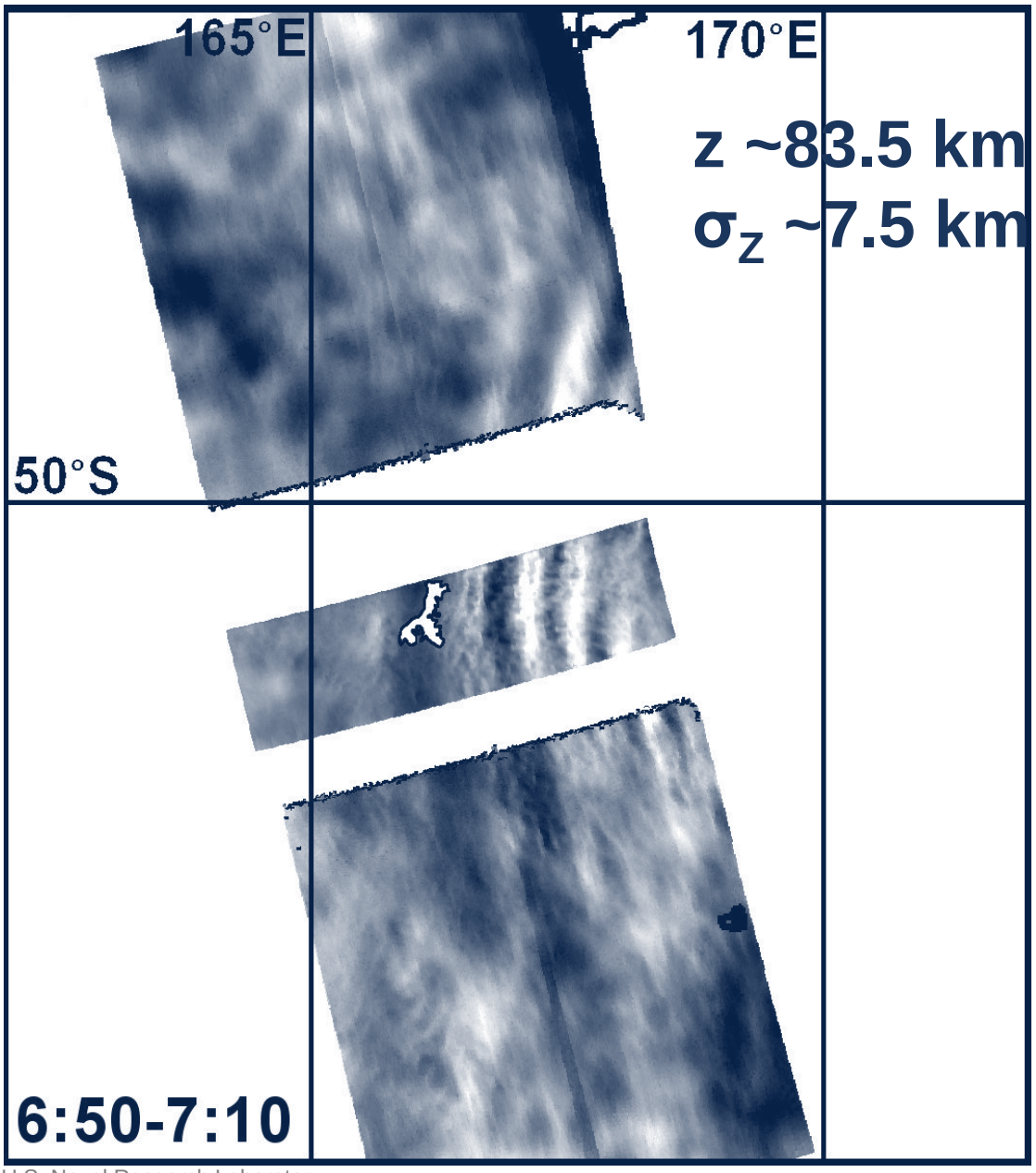
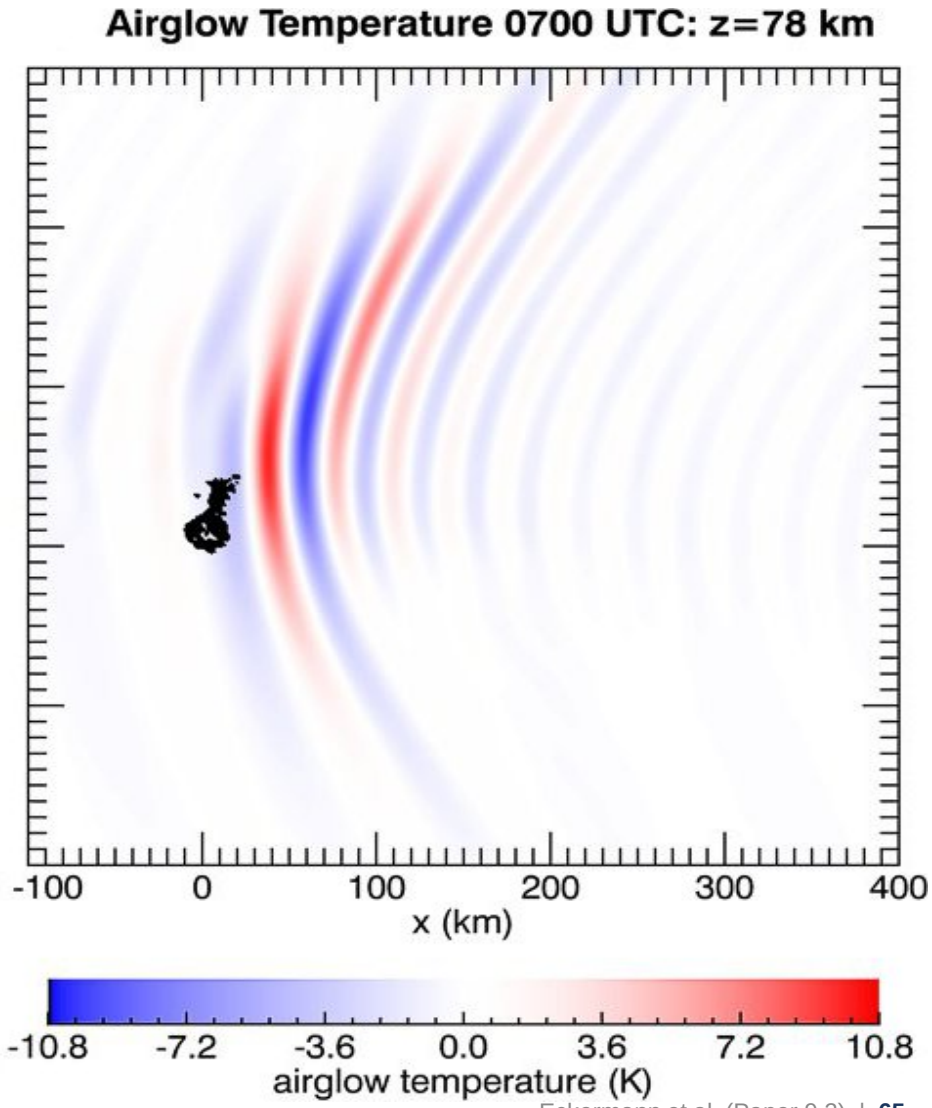
Life Cycle of RF22 Gravity Wave Event



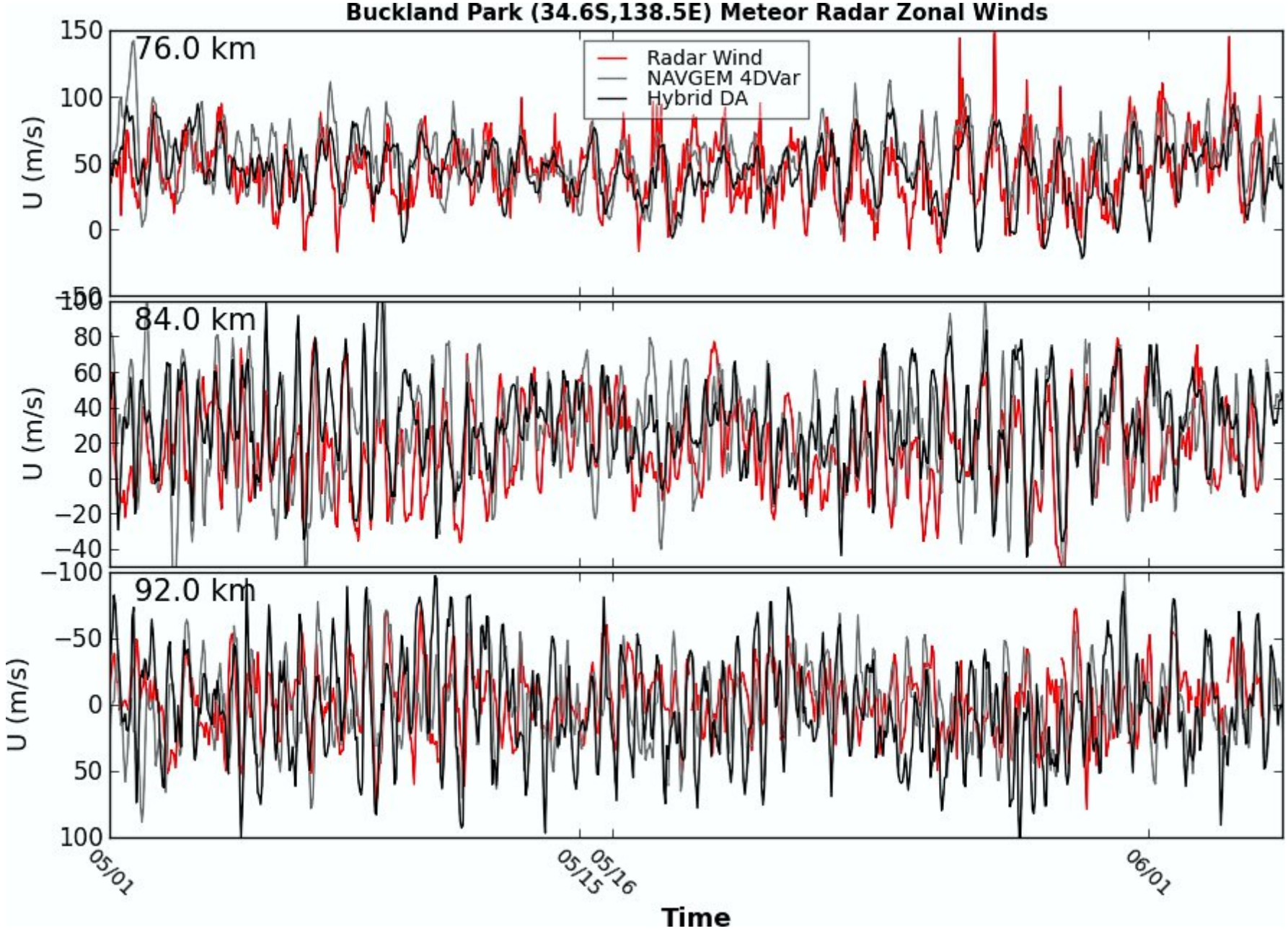
RF23 MLT Gravity Wave over the Auckland Islands: Eckermann et al. (JAS 2016)



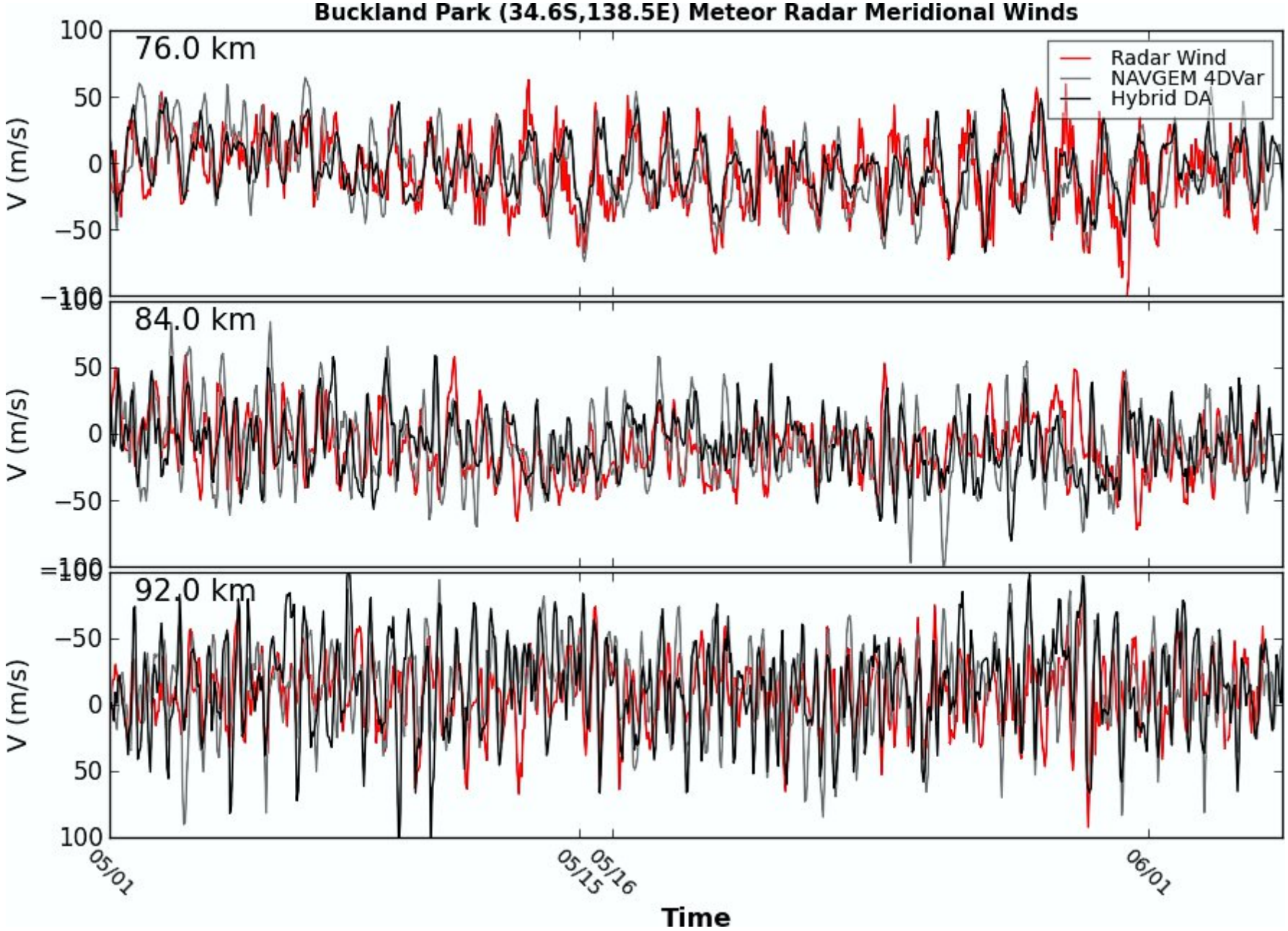
$$T'_{AG}(x,y) = \int I(z')T'(x,y,z')dz' \Big/ \int I(z')dz'$$



PRD Radar in Buckland Park Australia MLT Zonal Winds



PRD Radar in Buckland Park Australia MLT Meridional Winds



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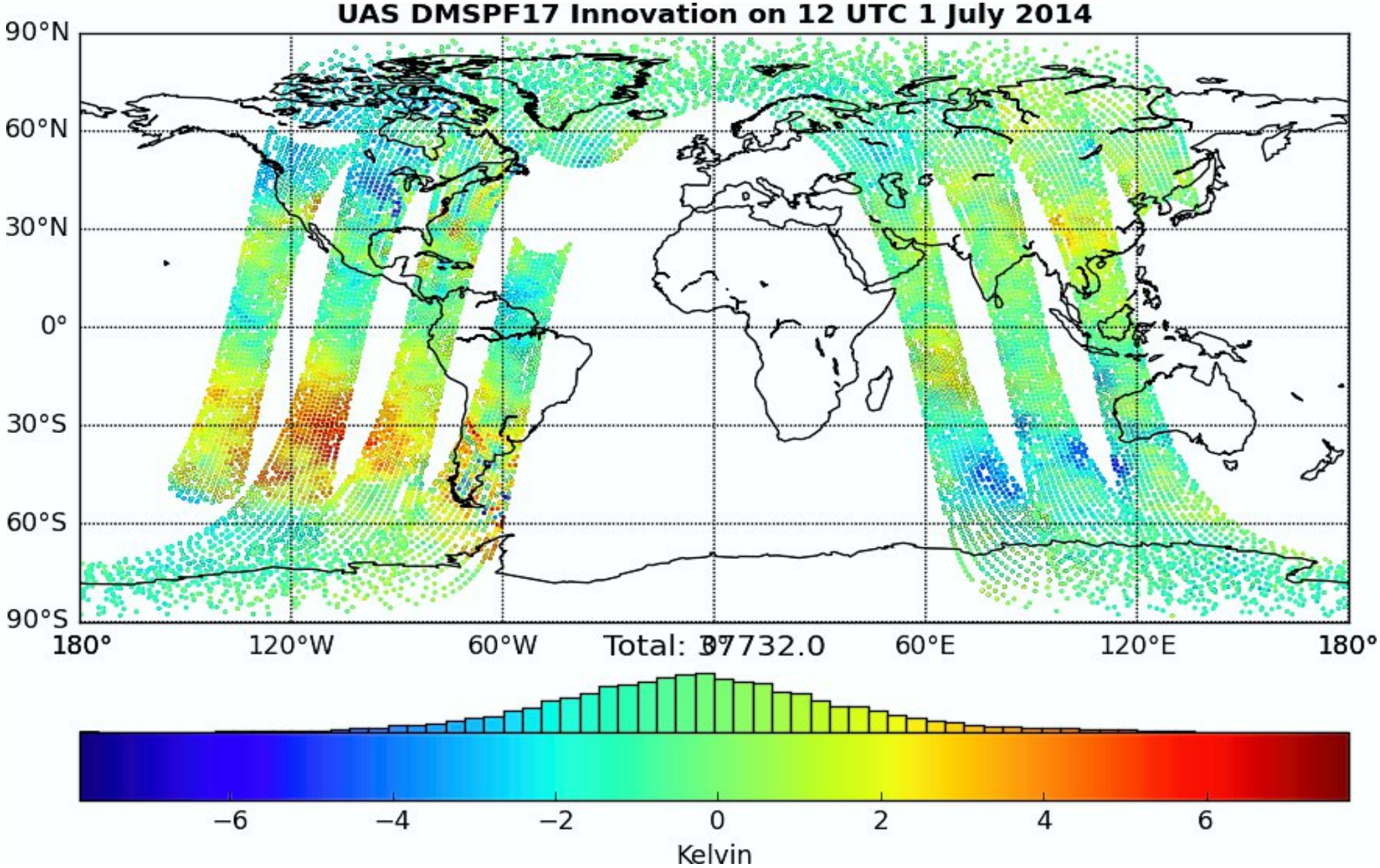
Sample Channel 20 SSMIS UAS Innovations



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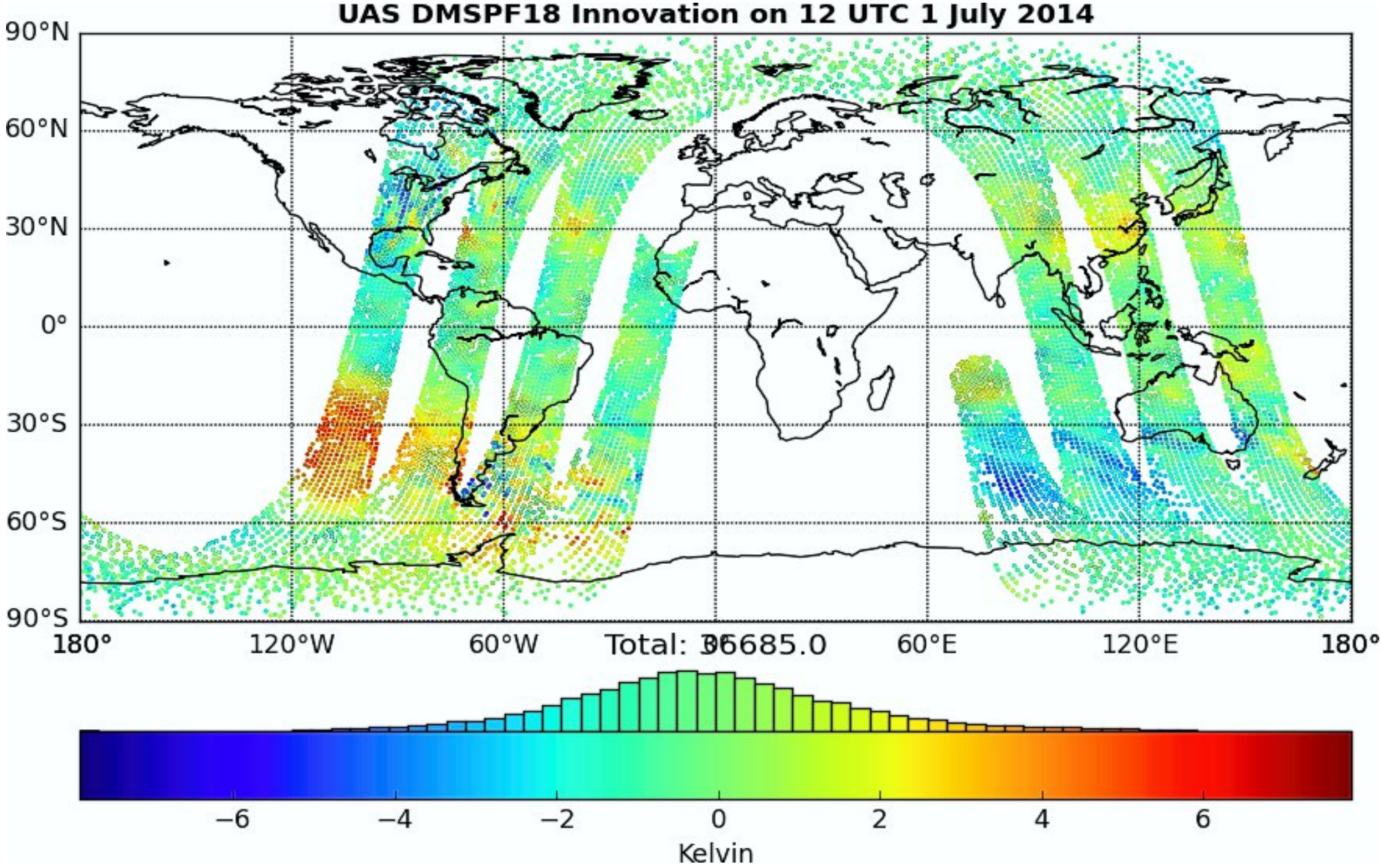
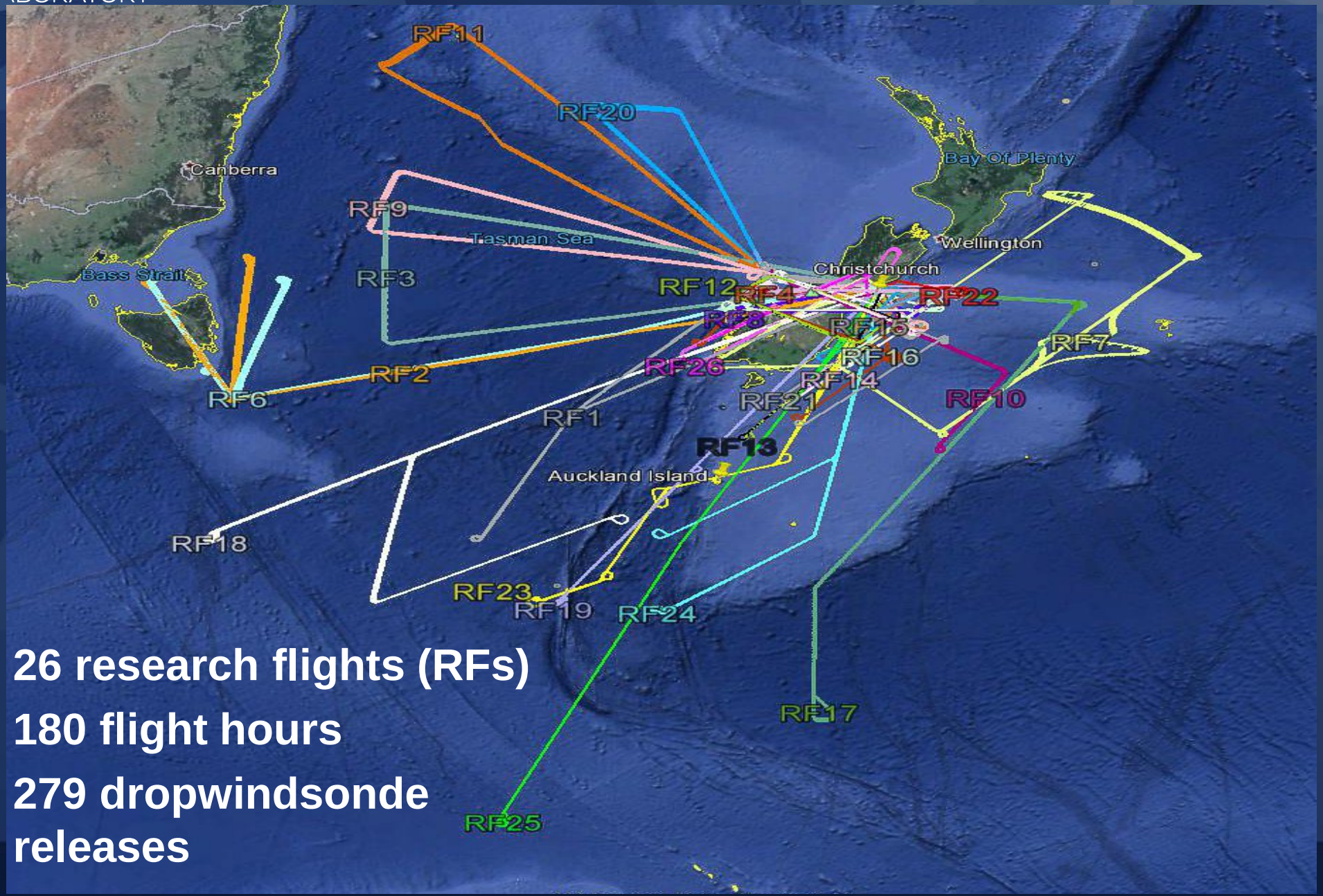
Sample Channel 20 SSMIS UAS Innovations



The Deep Propagating Gravity Wave Experiment: May-July 2014

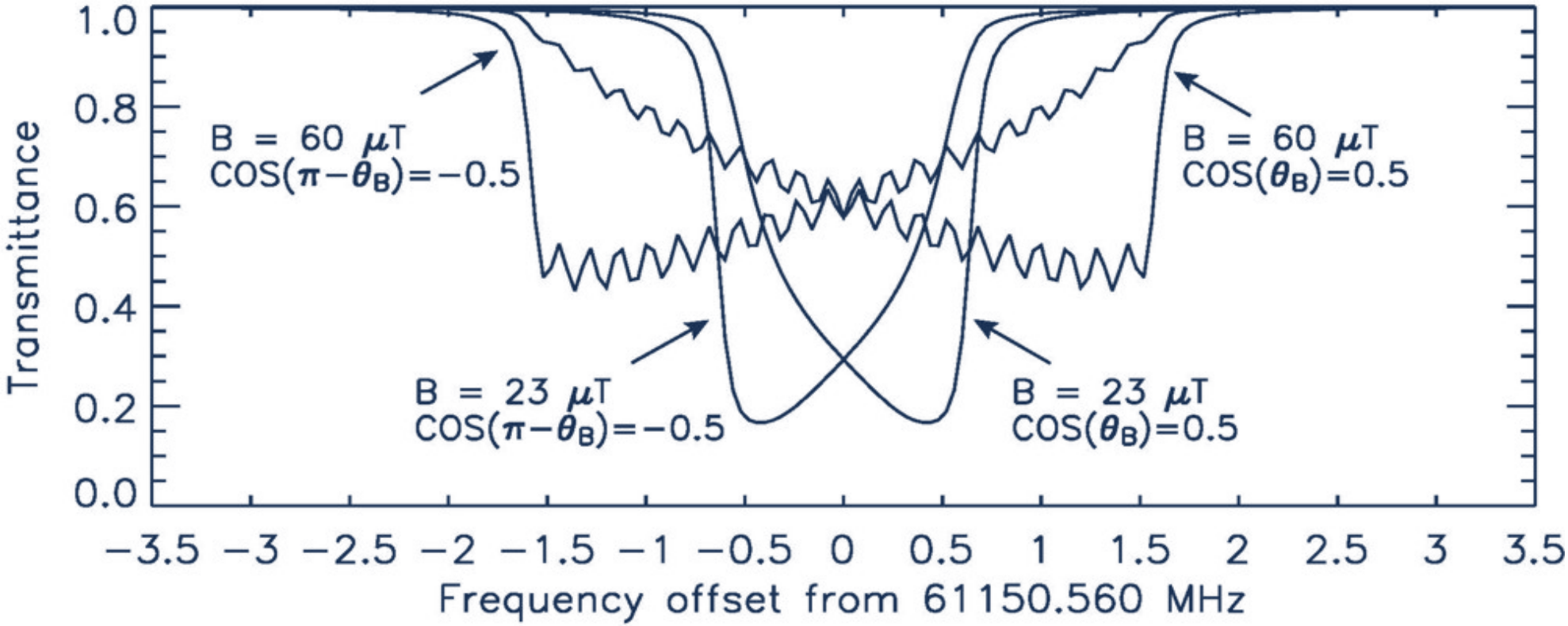


26 research flights (RFs)

180 flight hours

279 dropwindsonde releases

Zeeman Splitting of O2 60 GHz Lines by Geomagnetic Fields



- UAS channels 19–24 have narrow spectral bands located near line centers of O_2 magnetic dipole transitions
- Zeeman interaction of O_2 molecule's electronic spin with Earth's magnetic field causes these lines to split (e.g., Stogryn 1989)
- NAVGEM SSMIS radiance assimilation accounts for Zeeman splitting effects on radiative transfer in channels 19-24 based on geomagnetic field strengths, plus Doppler shift due to spacecraft motion and planetary rotation (JCSDA CRTM)

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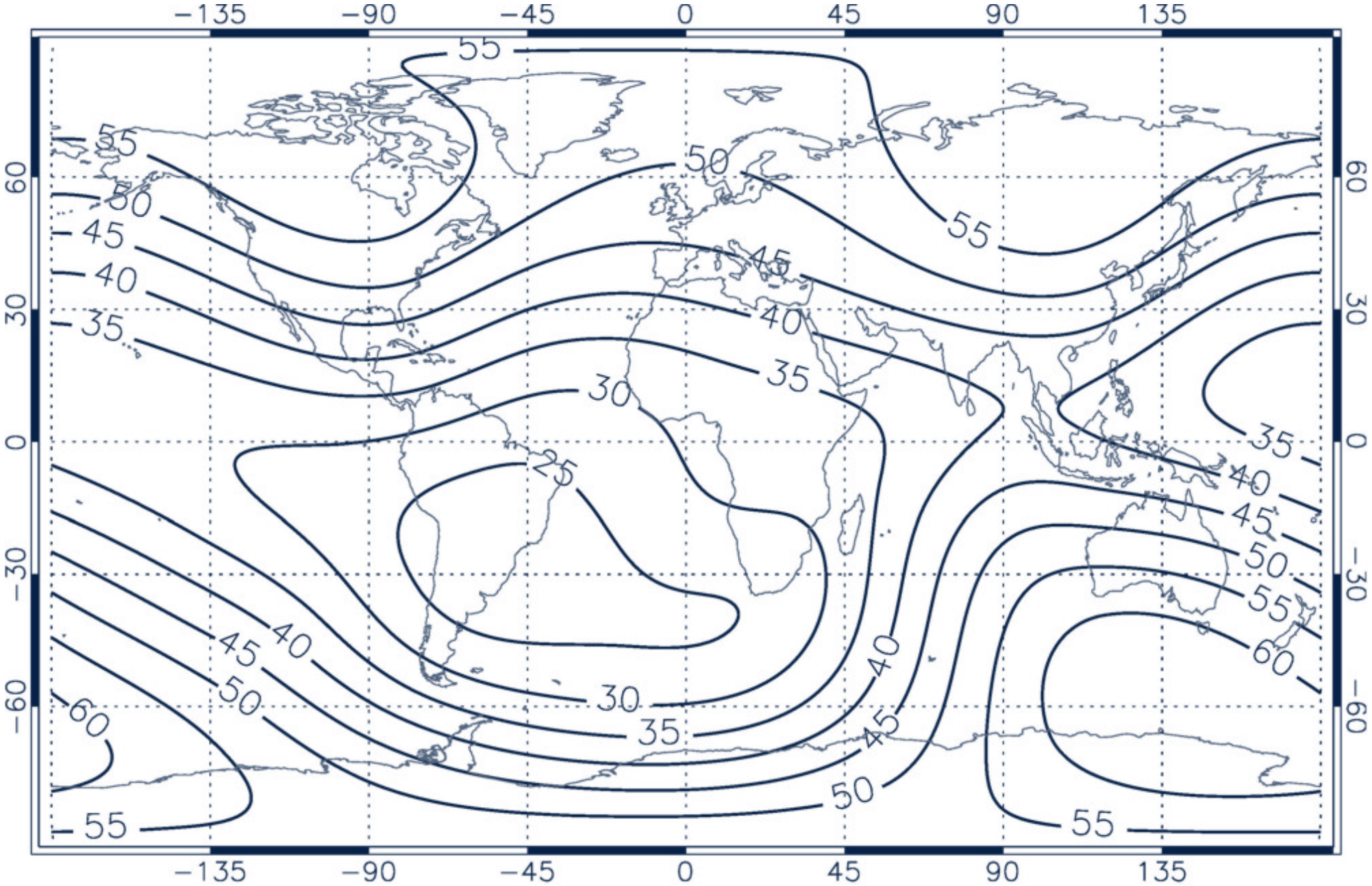
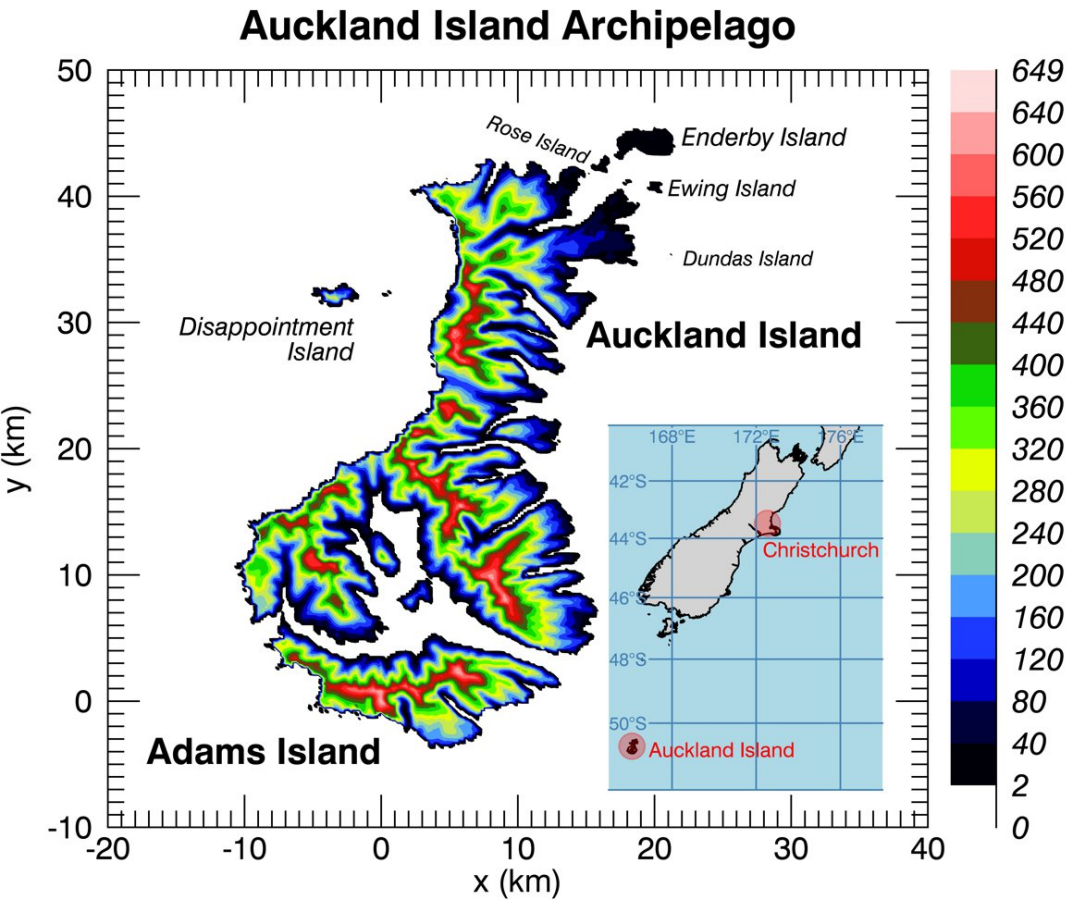
Typical Geomagnetic Field Strengths (μT) at ~60 km Altitude

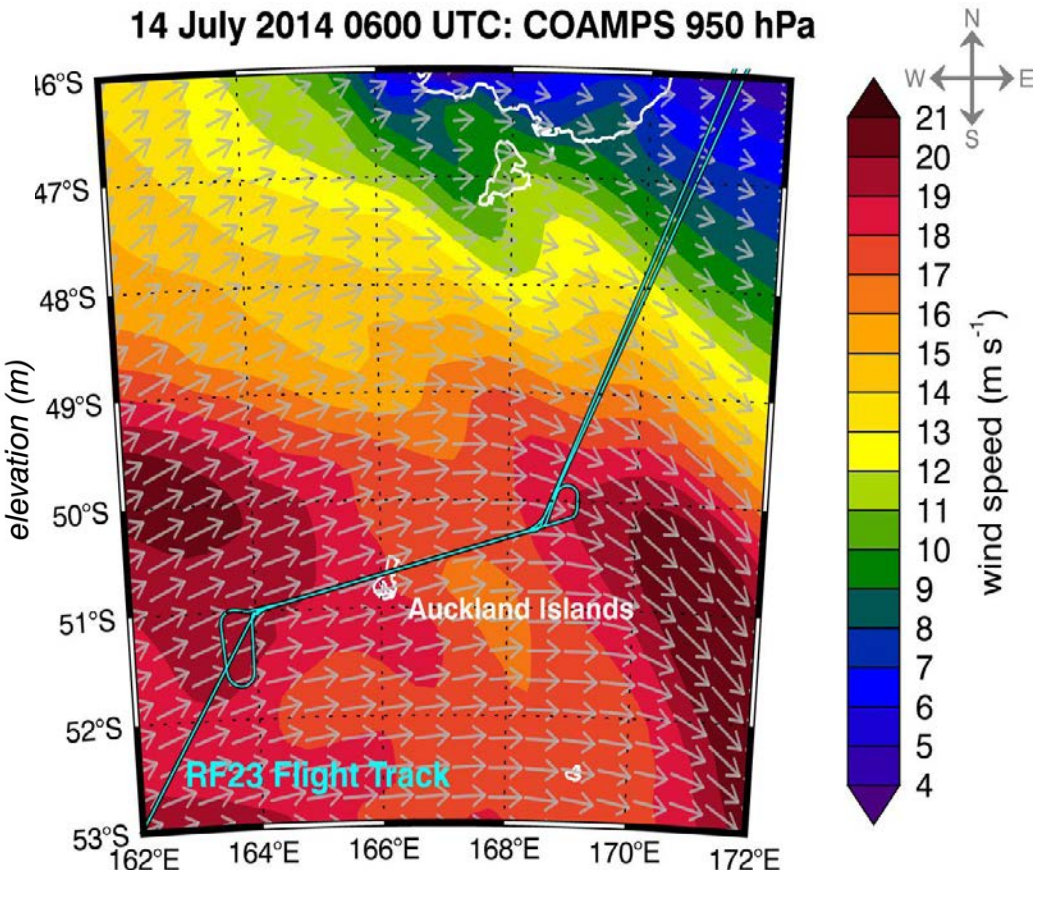


DEEPWAVE Research Flight 23 (RF23)

Movitation: Test hypothesis that persistent stratospheric “cold pole” biases in climate/NWP models may originate from drag due to deep-propagating orographic gravity waves from small subantarctic island chains that is currently missing in climate/NWP models (McLandress et al. JAS 2012; Alexander and Grimsdell JGR 2013)

Execution: 14 July 2014





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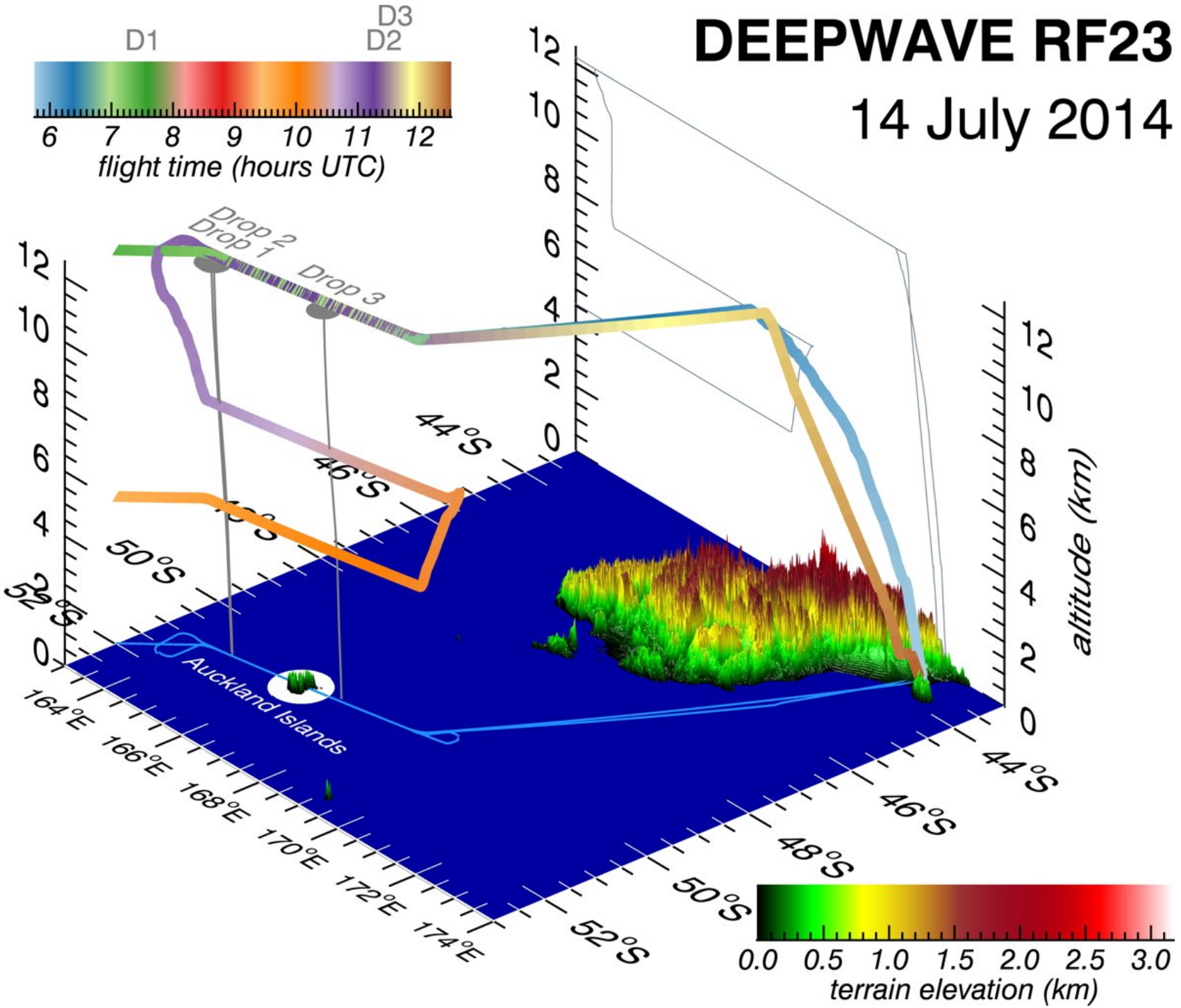
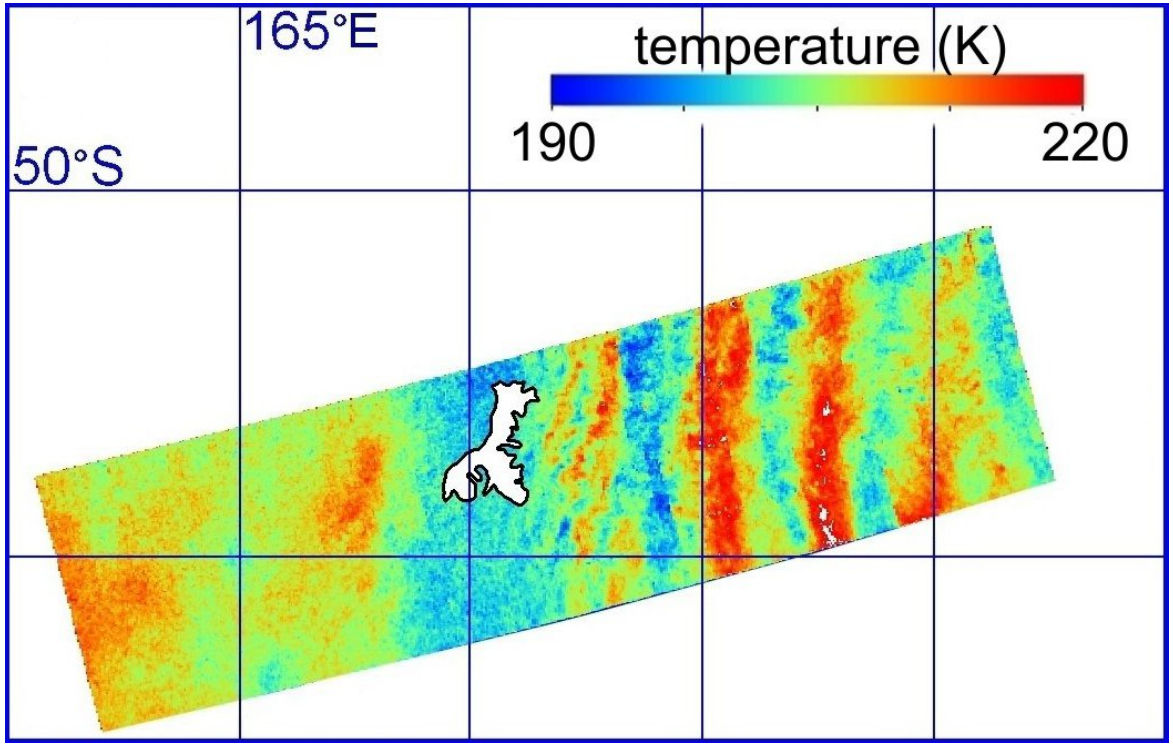


AMTM OH Airglow Imagery

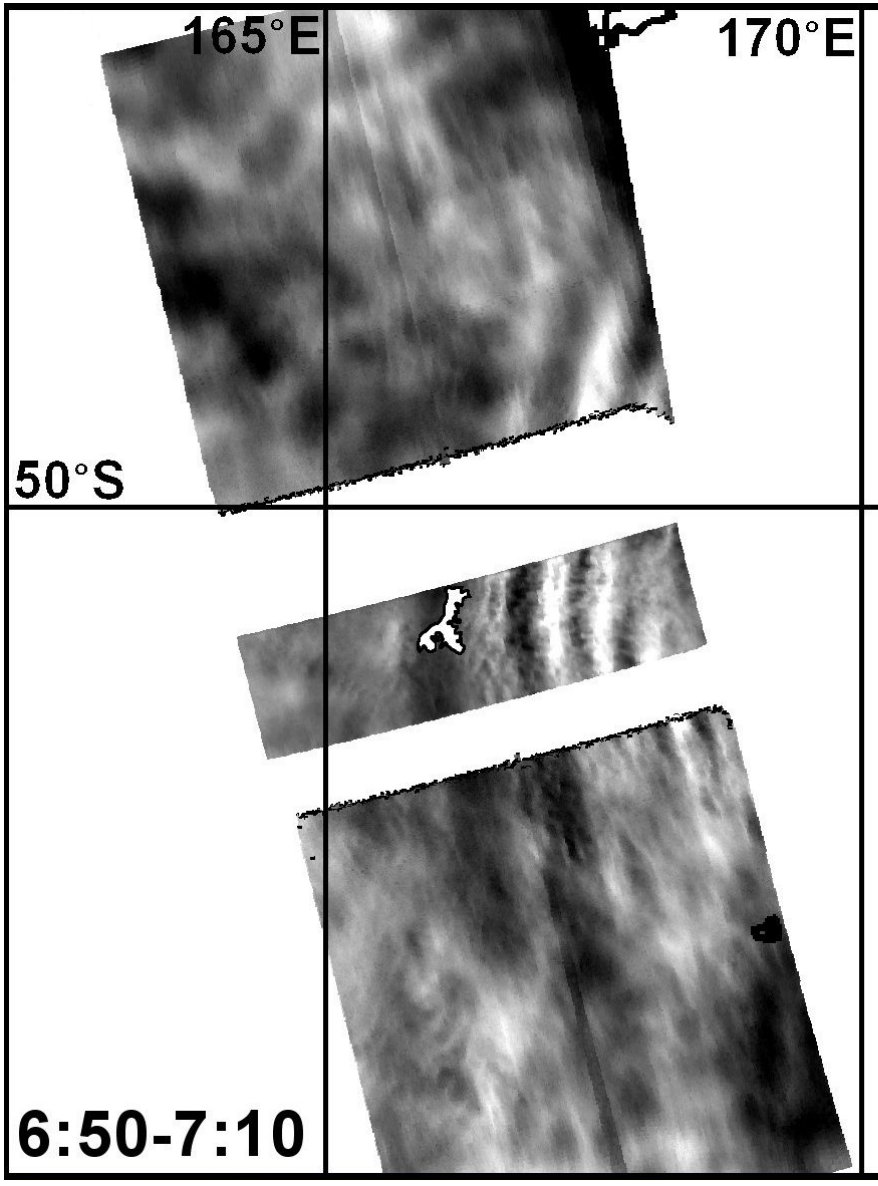
AMTM: Advanced Mesospheric Temperature Mapper

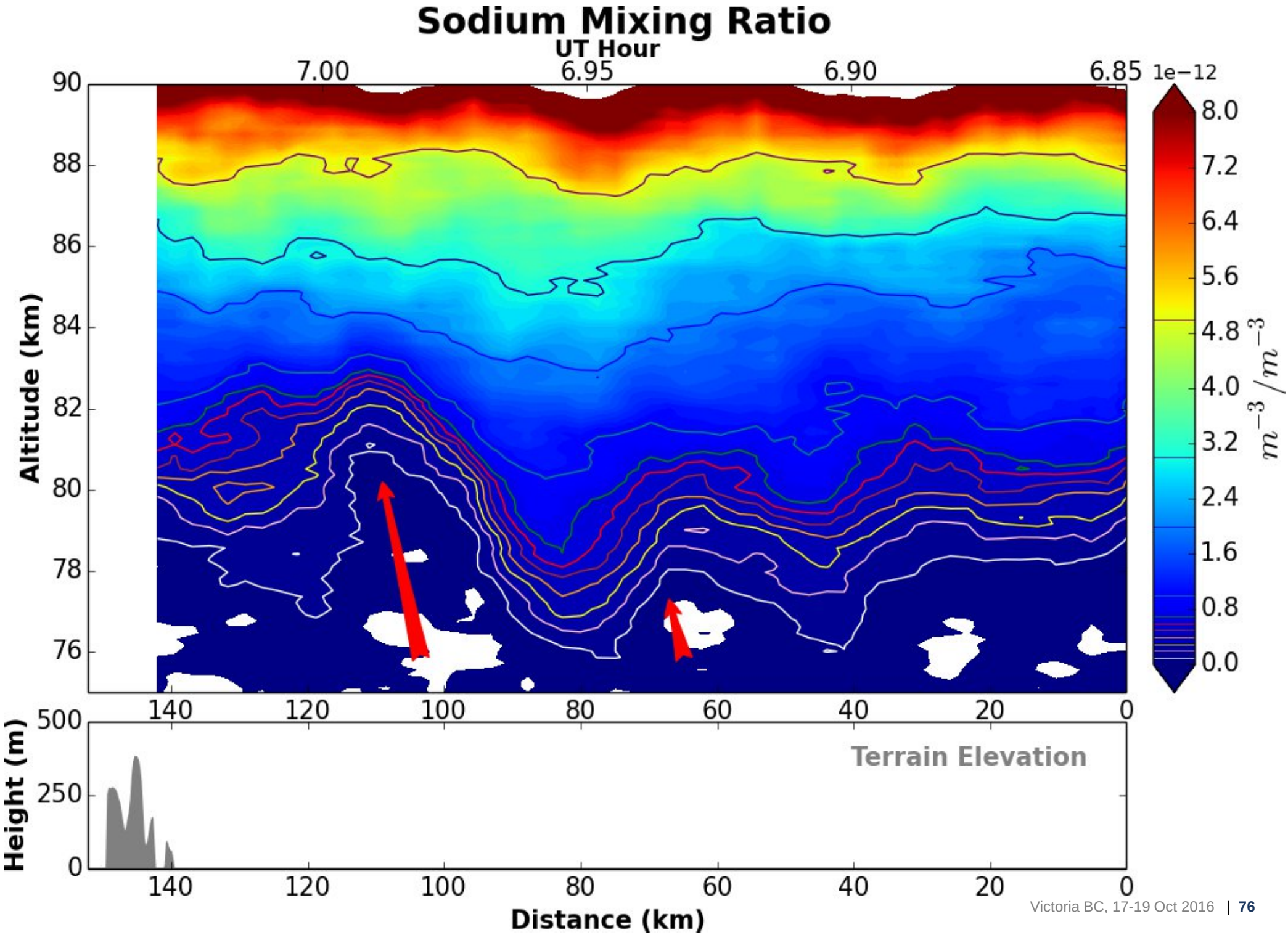
- Images OH Meinel emission in zenith and two “wing” cameras
- Temperatures retrieved from zenith camera data
- See Pautet et al. (JGR 2016) for details…

AMTM Temperature Retrieval

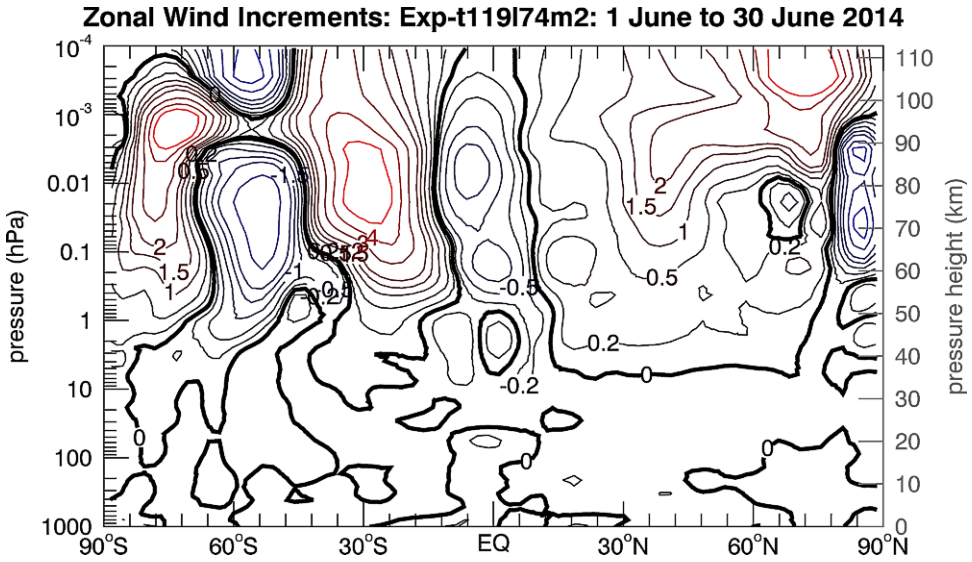


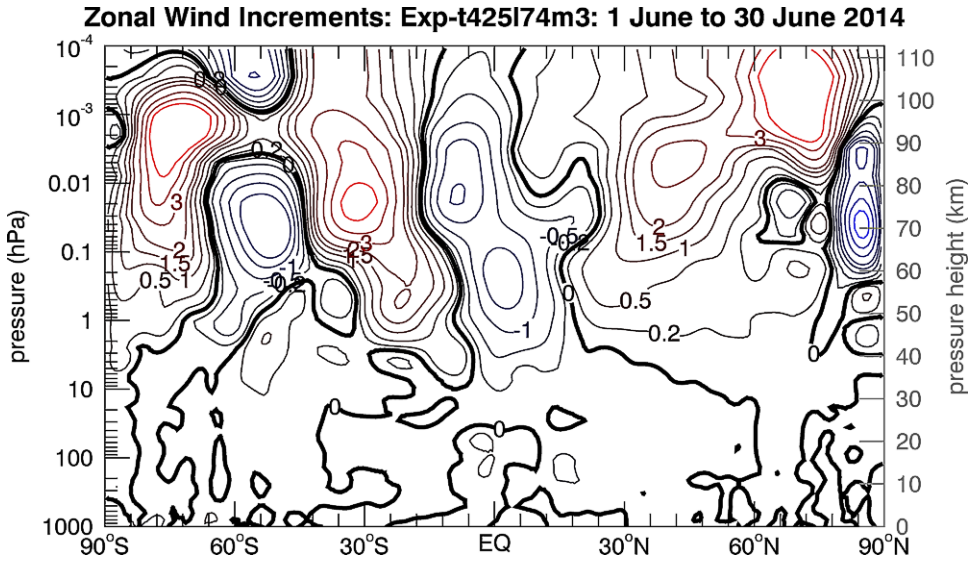
OH Airglow Intensity

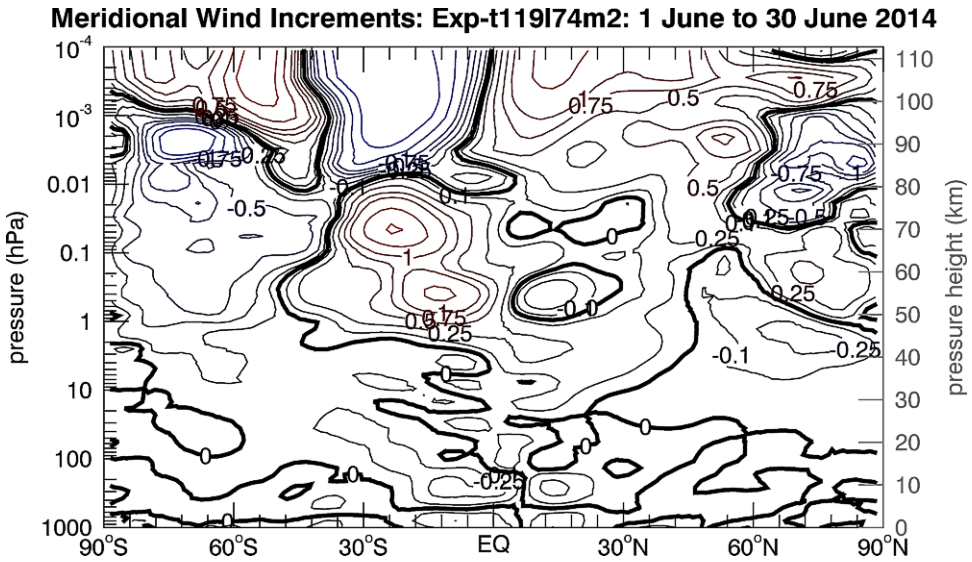


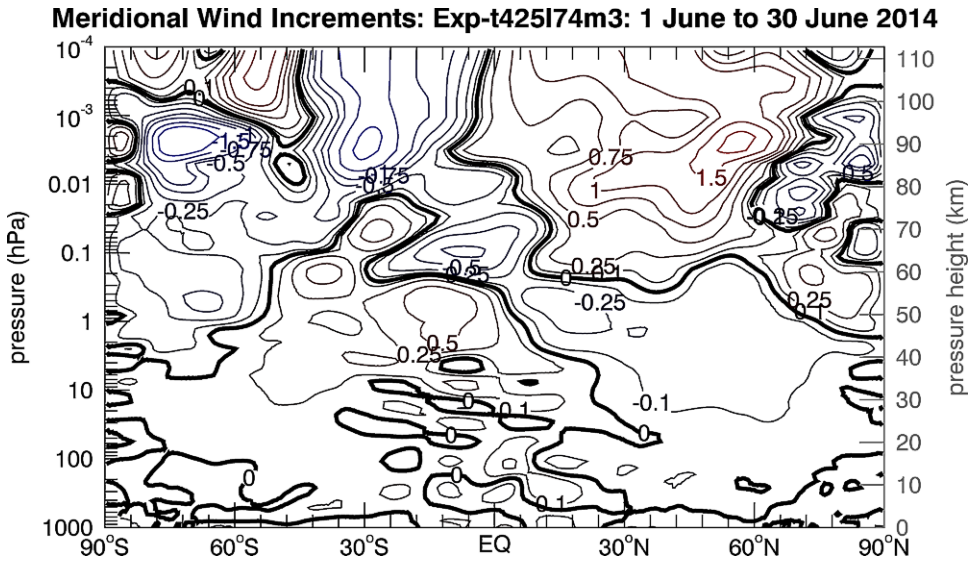

Sodium Mixing Ratio
UT Hour
7.00
6.95
6.90
6.85
1e−12
8.0
7.2
6.4
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0
m^{-3}/m^{-3}
Altitude (km)
90
88
86
84
82
80
78
76
140
120
100
80
60
40
20
0
Height (m)
500
250
0
Terrain Elevation
Distance (km)

June Zonal vs. Meridional Wind Increments 4DVAR Experiments

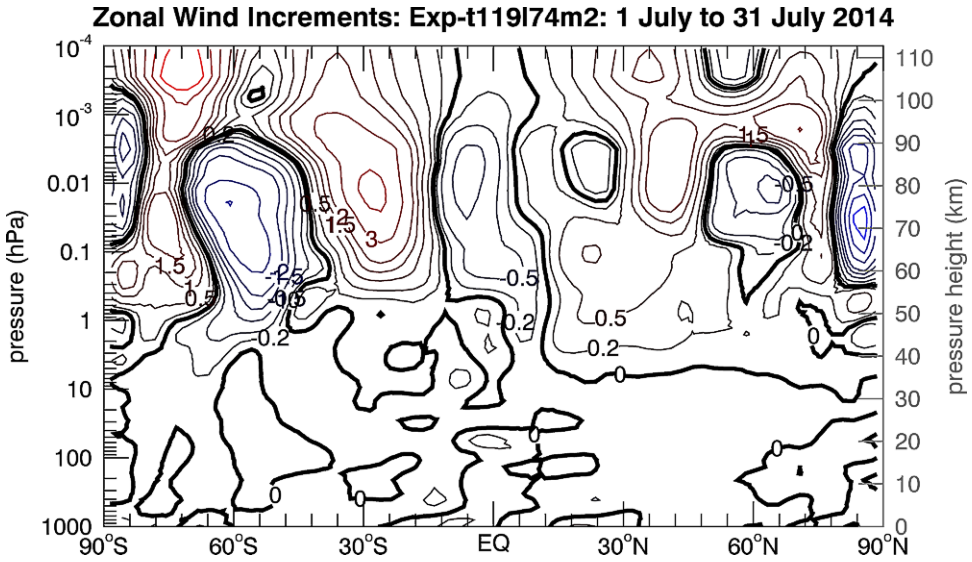


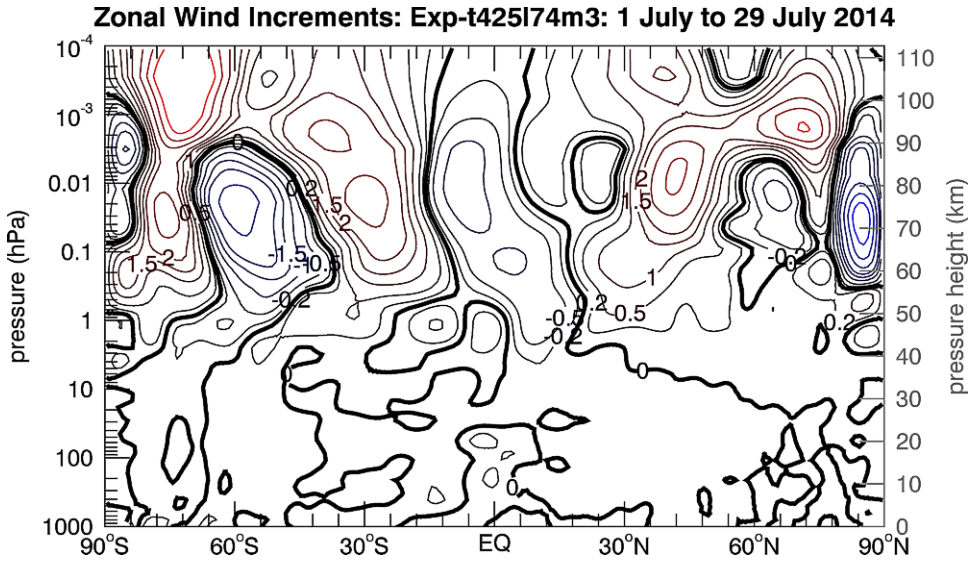


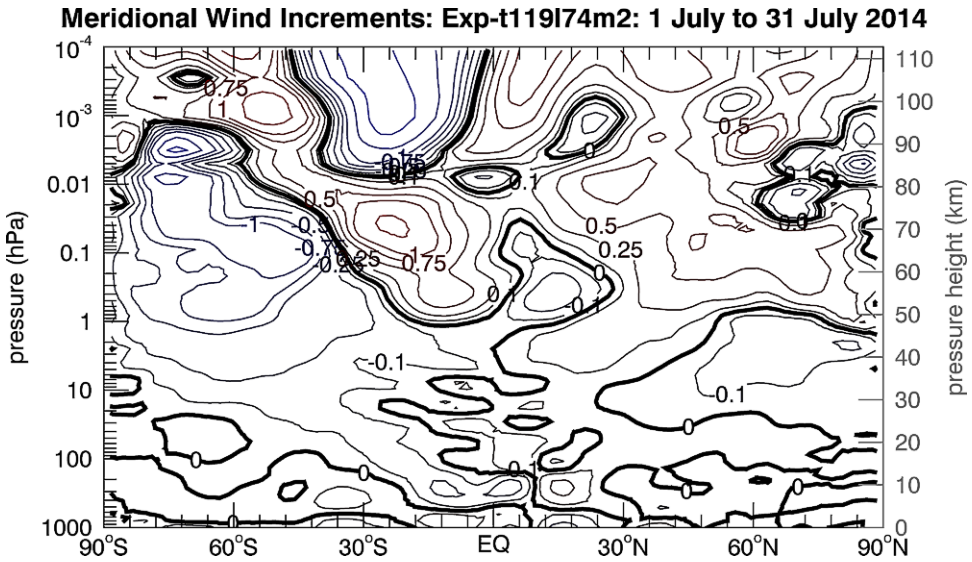


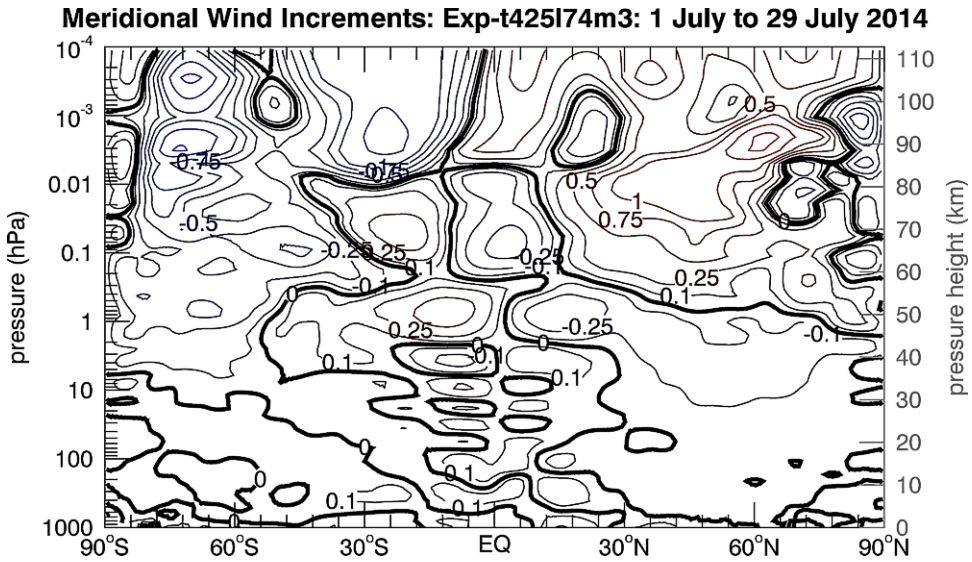


July Zonal vs. Meridional Wind Increments 4DVAR Experiments

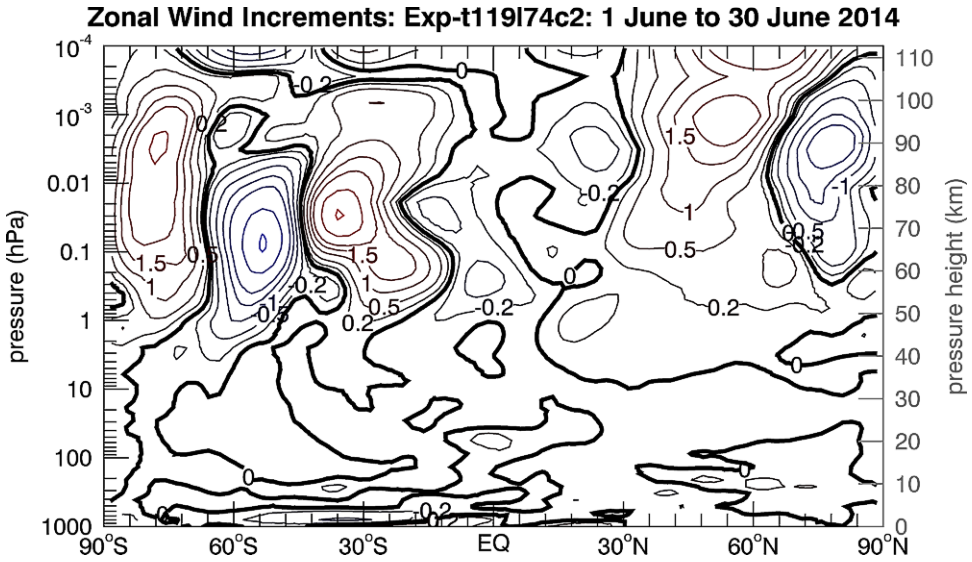


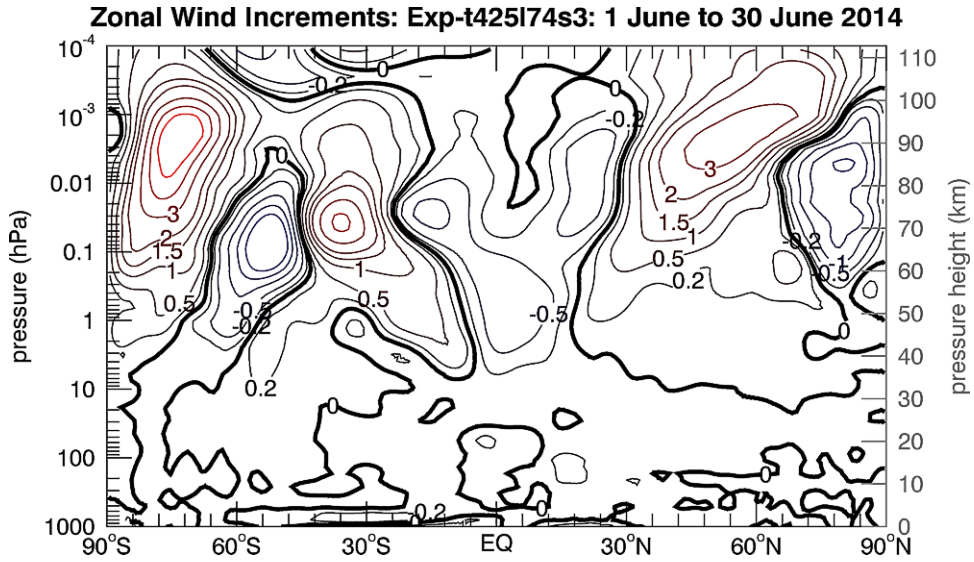


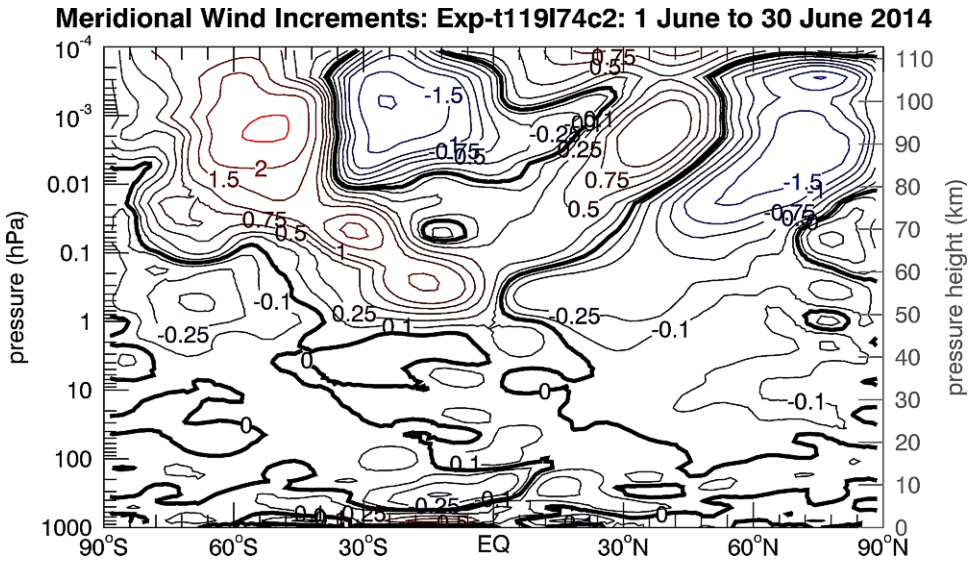


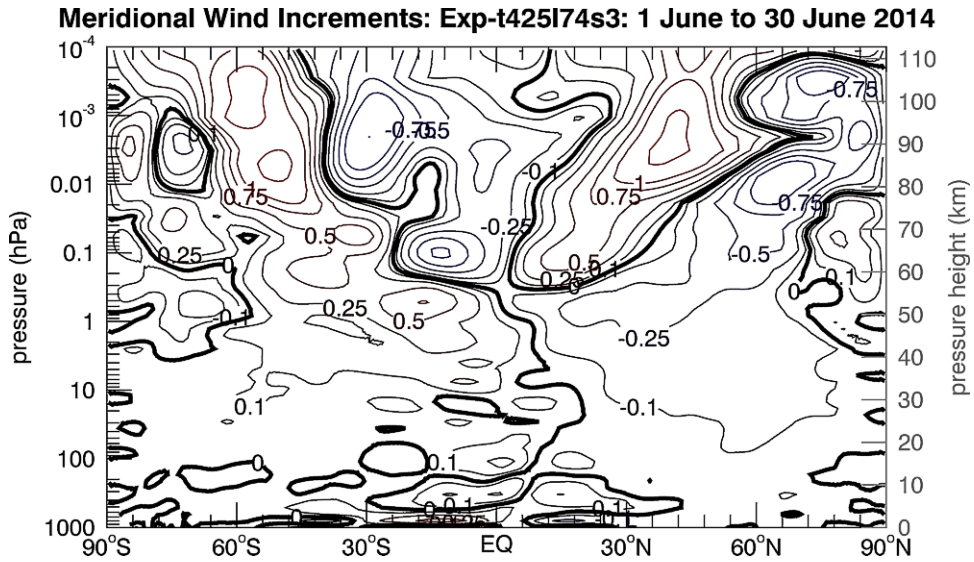


June Zonal vs. Meridional Wind Increments Hybrid Experiments

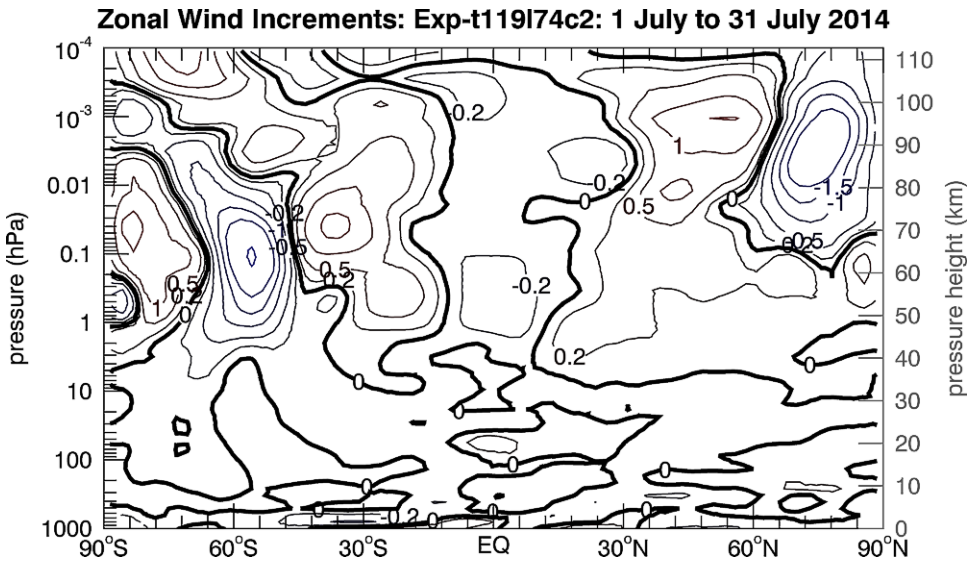


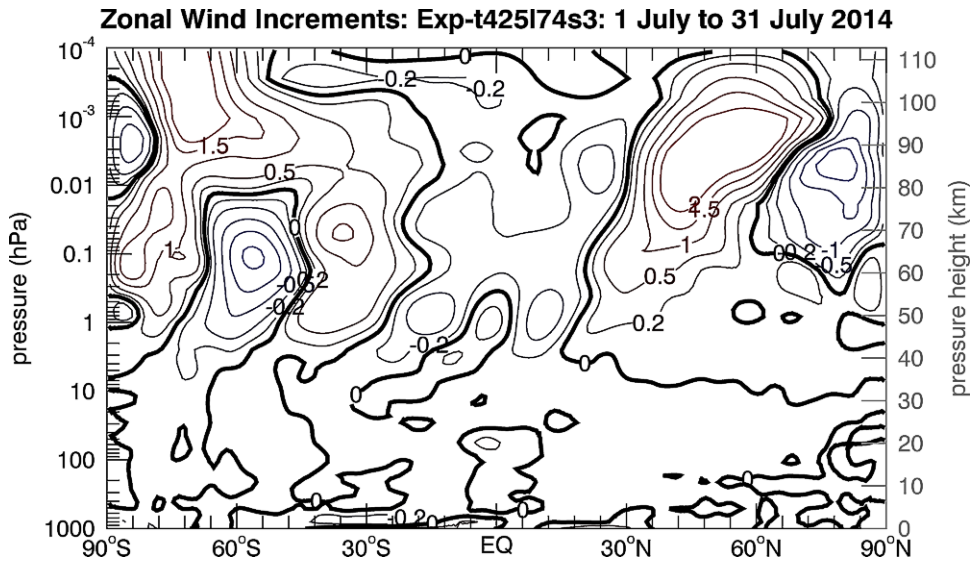


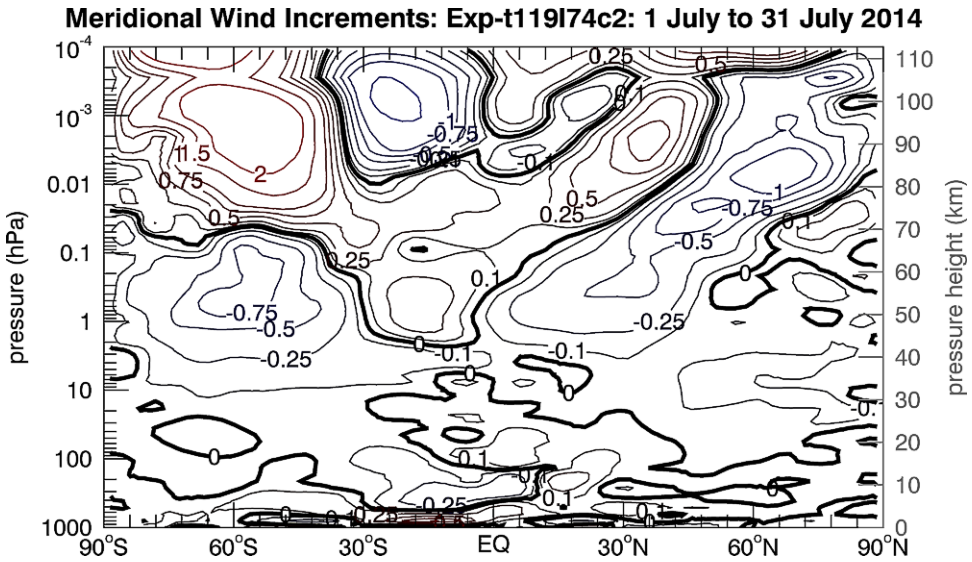


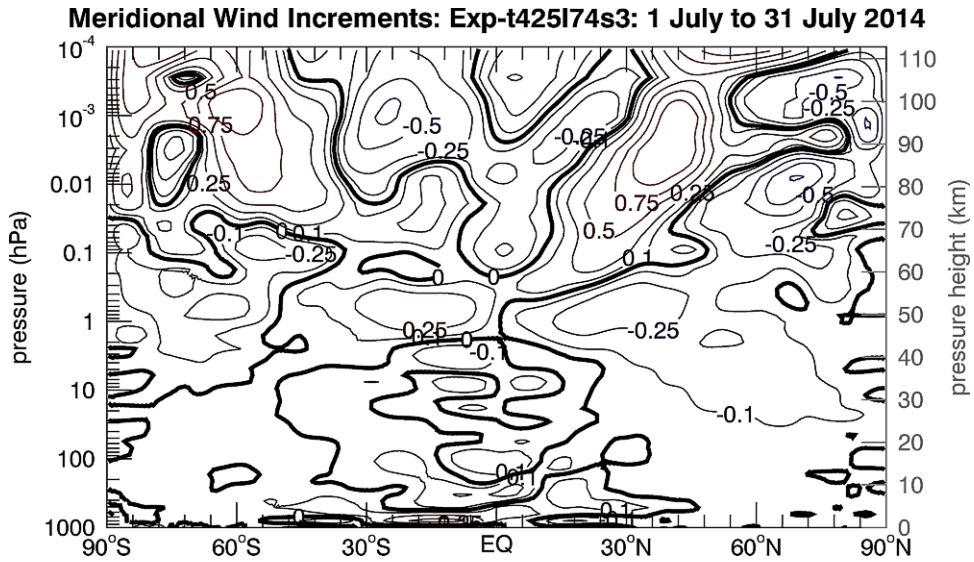


July Zonal vs. Meridional Wind Increments Hybrid Experiments









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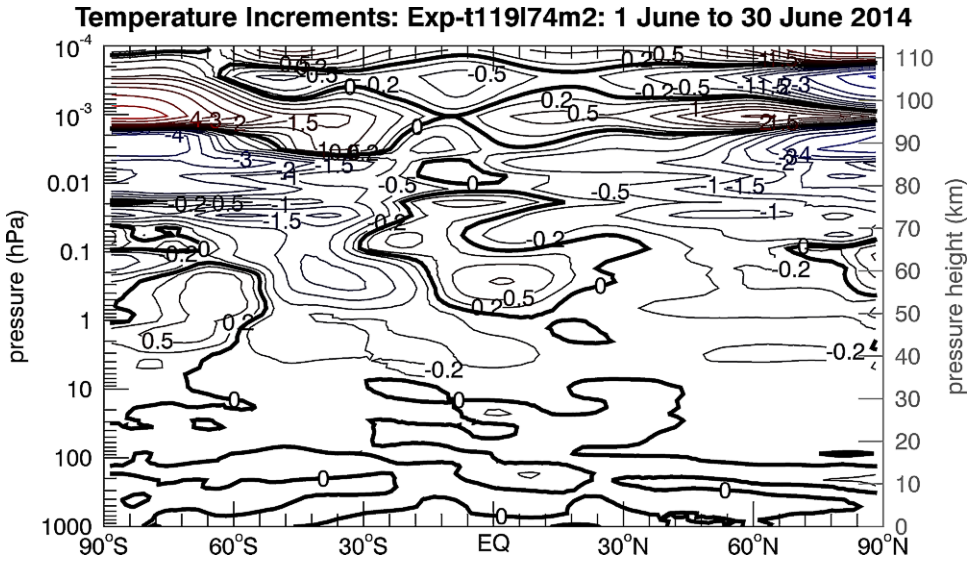
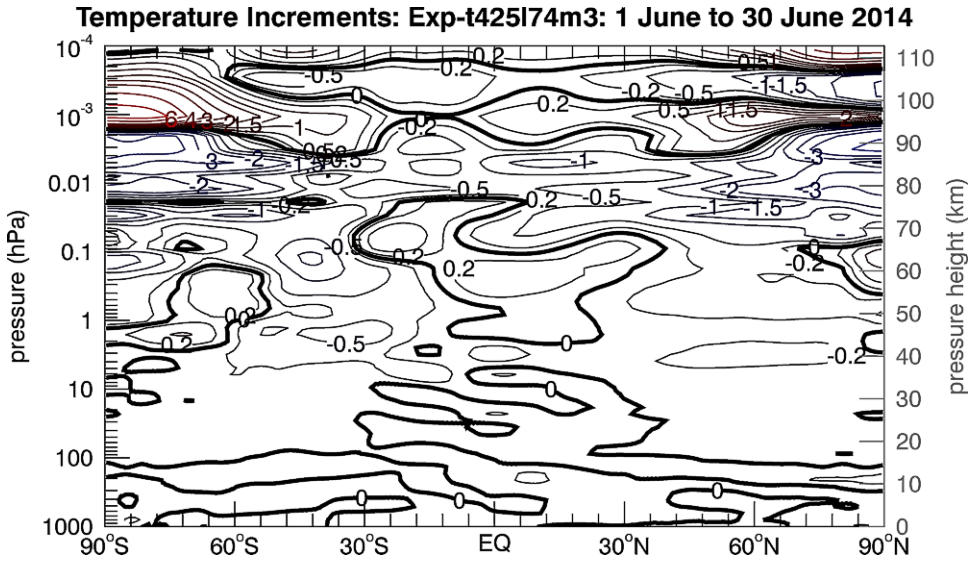
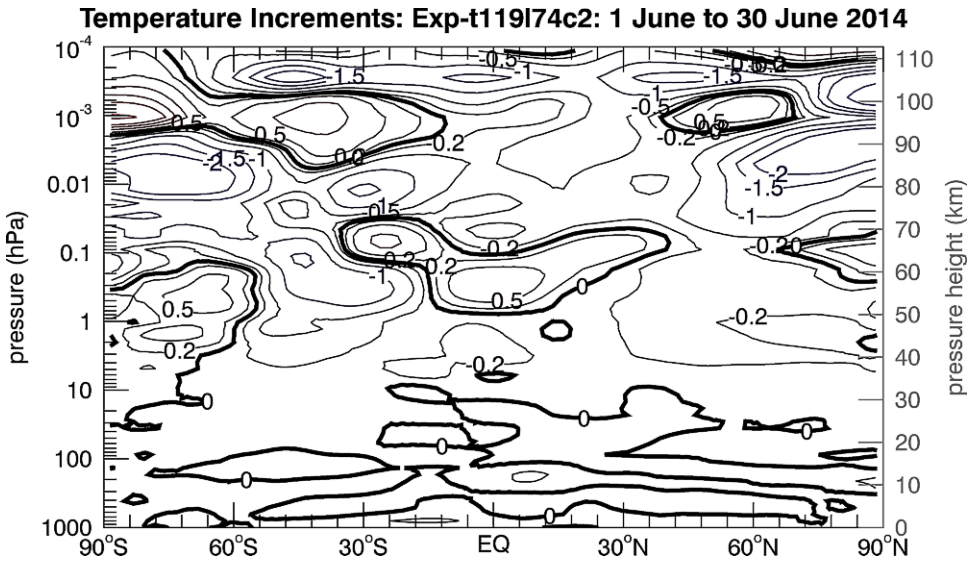
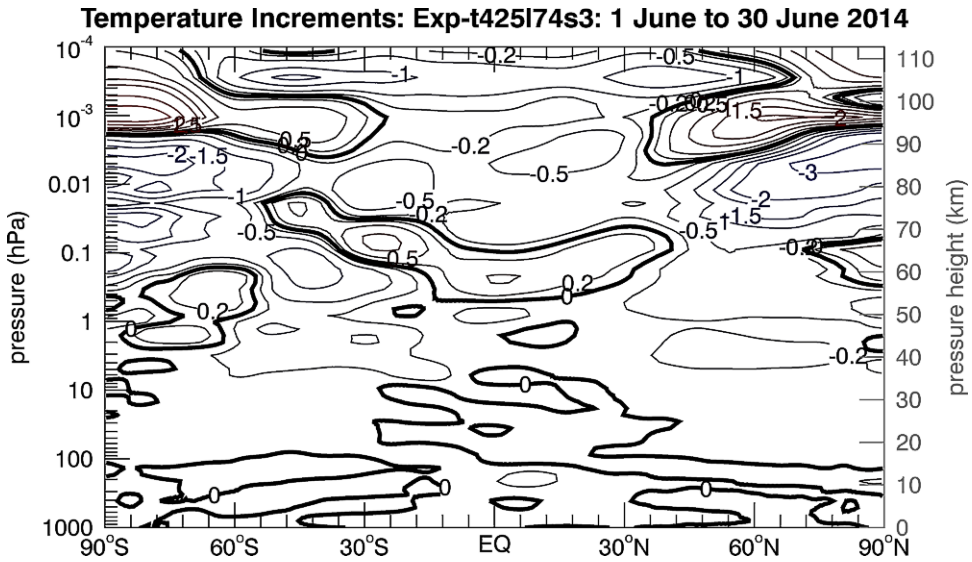
June Zonal-Mean Temperature Increments









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July Zonal-Mean Temperature Increments