The Arctic Vortex in March 2011: A Dynamical Perspective

Margaret M. Hurwitz [1,2], **Paul A. Newman** [2], and **Chaim I. Garfinkel** [3]

1   *Goddard Earth Sciences Technology and Research (GESTAR), Morgan State University, Baltimore, MD, USA*

2   *NASA Goddard Space Flight Center, Greenbelt, MD, USA*

3   *Johns Hopkins University, Baltimore, MD, USA*

In late winter in the Arctic stratosphere, ozone loss is closely tied to temperature: Ozone-depleting substances (e.g., CFCs) are activated on polar stratospheric clouds, which form only at very low temperatures. Variability in polar lower stratospheric temperature is highly correlated with the year–to–year variability in large–scale wave driving from the troposphere.

Record ozone loss was observed in March 2011. This paper documents the dynamical conditions associated with this event: Weak wave driving in February preceded cold anomalies in the polar lower stratosphere in March and a relatively late winter–to–spring transition in April. The 2011 conditions were unusual with respect to the 1979–2011 satellite era, but not unprecedented. Similarly severe ozone loss, low temperatures and weak wave driving were observed in March 1997.

In March 2011, El Niño/Southern Oscillation was in its cold phase (i.e., La Niña) while the quasi–biennial oscillation (QBO), an alternating east–west wind pattern in the equatorial lower stratosphere, was in its westerly phase. Though both of these conditions are generally associated with a colder lower stratosphere in mid–winter, the respective cold anomalies do not persist through March. Therefore, the La Niña and QBO–westerly conditions cannot explain the observed cold anomalies in March 2011. In contrast, positive sea surface temperature anomalies in the North Pacific may have contributed to the unusually weak tropospheric wave driving and cold Arctic stratosphere in late winter 1997 and 2011.

University, Baltimore, MD, USA

2   *NASA Goddard Space Flight Center, Greenbelt, MD, USA*

3   *Johns Hopkins University, Baltimore, MD, USA*

In late winter in the Arctic stratosphere, ozone loss is closely tied to temperature: Ozone–depleting substances (e.g., CFCs) are activated on polar stratospheric clouds, which form only at very low temperatures. Variability in polar lower stratospheric temperature is highly correlated with the year–to–year variability in large–scale wave driving from the troposphere.

Record ozone loss was observed in March 2011. This paper documents the dynamical conditions associated with this event: Weak wave driving in February preceded cold anomalies in the polar lower stratosphere in March and a relatively late winter–to–spring transition in April. The 2011 conditions were unusual with respect to the 1979–2011 satellite era, but not unprecedented. Similarly severe ozone loss, low temperatures and weak wave driving were observed in March 1997.

1 # The Arctic Vortex in March 2011: A Dynamical Perspective

2

3 **Margaret M. Hurwitz [1,2], Paul A. Newman [2] and Chaim I. Garfinkel [3]**

4

5 [1]   {Goddard Earth Sciences Technology and Research (GESTAR), Morgan State
6   University, Baltimore, MD, USA}
7 [2]   {NASA Goddard Space Flight Center, Greenbelt, MD, USA}
8 [3]   {Johns Hopkins University, Baltimore, MD, USA}

9

10 Correspondence to: Margaret M. Hurwitz (margaret.m.hurwitz@nasa.gov)

11

11 **Abstract**

12 Despite the record ozone loss observed in March 2011, dynamical conditions in the Arctic
13 stratosphere were unusual but not unprecedented. Weak planetary wave driving in February
14 preceded cold anomalies in the polar lower stratosphere in March and a relatively late breakup of
15 the Arctic vortex in April. La Niña conditions and the westerly phase of the quasi–biennial
16 oscillation (QBO) were observed in March 2011. Though these conditions are generally
17 associated with a stronger vortex in mid–winter, the respective cold anomalies do not persist
18 through March. Therefore, the La Niña and QBO–westerly conditions cannot explain the
19 observed cold anomalies in March 2011. In contrast, positive sea surface temperature anomalies
20 in the North Pacific may have contributed to the unusually weak tropospheric wave driving and
21 strong Arctic vortex in late winter 2011.

22

1   Introduction

In the Arctic stratosphere, chemical ozone loss takes place each year in the late winter (WMO, 2011).   Arctic ozone loss represents the interaction between chemistry and climate: heterogeneous ozone depletion on polar stratospheric clouds requires the presence of halogens, sunlight and low temperatures.   Rex et al. (2004 and 2006) calculated that the severity of large ozone loss events has been increasing over the last few decades, and speculated that increased radiative cooling by greenhouse gases plays a role.

Severe ozone loss was observed in the Arctic stratosphere in 2011.   On March 14th, the Alfred Wegener Institute (AWI) in Germany reported that "unusually low temperatures in the Arctic ozone   layer   have   recently   initiated   massive   ozone   depletion" (http://www.awi.de/en/news/press_releases).   Figure 1a shows that March 2011 monthly mean total ozone value was the lowest of the satellite era (total ozone dataset updated from Stolarski and Frith, 2006).   On April 8th, Science Daily reported "unprecedented" Arctic ozone depletion, caused   by   unusual   and   persistent   cold   conditions   in   the   Arctic   vortex (http://www.sciencedaily.com/releases/2011/04/110406085634.htm).   Researchers at AWI noted that the anomalous ozone loss and low temperatures in March 2011 were consistent with the estimated pattern of "cold winters getting colder" (Rex et al., 2004 and 2006).

Two sources of interannual variability in the Arctic lower stratosphere in winter are El Niño/Southern Oscillation (ENSO) and the phase of the quasi–biennial oscillation (QBO). Holton and Tan (1980) and Lu et al. (2008) showed that the phase of the QBO modulates the region in which planetary waves can propagate in the stratosphere, thus affecting the strength of the Arctic vortex in mid–winter.   The vortex is strongest during the westerly phase of the QBO. Similarly, planetary wave driving is stronger during El Niño (ENSO warm phase) events than during La Niña (ENSO cold phase) events (e.g., Garfinkel and Hartmann, 2008).

The goals of this paper are to document the dynamical conditions in the Arctic stratosphere in March 2011 and attribute these conditions to known sources of dynamical variability.   Section 2 will describe the datasets and diagnostics used to perform this analysis.   In Section 3, March 2011 will be examined in the context of the satellite era.   The relationship of March conditions in

53   the Arctic stratosphere to ENSO and the phase of the QBO will be considered. In addition, the

54   possible role of North Pacific sea surface temperature variability in the anomalous dynamical

55   conditions in the Arctic vortex in March 2011 will be examined. Section 4 will provide a brief

56   summary and discussion.

57

58   **2   Data and diagnostics**

59   Sea surface temperature (SST) and atmospheric diagnostics are used to understand conditions in

60   the Arctic stratosphere in March 2011. The present analysis spans the satellite era (1979–2011)

61   and focuses on the Northern Hemisphere mid– to late winter (January through March). Zonal

62   winds, temperature and eddy heat flux fields are derived from the National Centers for

63   Environmental Prediction (NCEP)–U.S. Department of Energy (DOE) reanalysis (NCEP–2)

64   (Kanamitsu et al., 2002). The NCEP–2 reanalysis has $2.5° \times 2.5°$ horizontal resolution and

65   vertical coverage up to 10 hPa.

66

67   The phase of the quasi–biennial oscillation (QBO) is characterized by zonal winds in the

68   equatorial region at 50 hPa. Monthly mean values of the 50–hPa QBO index

69   (http://www.cpc.ncep.noaa.gov/data/indices/qbo.u50.index) are used in this study.

70

71   The springtime breakup of the Arctic vortex is calculated for each year. On the 450 K isentropic

72   surface (i.e., in the lower stratosphere), the breakup date is defined as the date when the five–day

73   running mean of zonal winds at the vortex edge falls below approximately 15.2 m s^{-1}, following

74   the criteria of Nash et al. (1996). The present analysis considers breakup dates based on the

75   NCEP–1 (Kalnay et al., 1996), NCEP–2 and NOAA Climate Prediction Center (CPC) (Gelman

76   et al., 1986; Nagatani et al., 1988; Finger et al., 1993) meteorological reanalyses.

77

78   Monthly mean SST fields are taken from the Hadley Centre Global Sea Ice and Sea Surface

79   Temperature (HadISST1) dataset (Rayner et al., 2003). Sea surface temperature anomalies in the

80   eastern equatorial Pacific are characterized by the Niño 3.4 index (see

81   http://www.cpc.noaa.gov/data/indices). Trenberth (1997) defines a conventional El Niño event

82   as a sustained period (usually six months or more) when the Niño 3.4 index exceeds 0.4, while a

83   La Niña event is defined as a sustained period when the Niño 3.4 index is less than –0.4.

84

3 Results

3.1 March 2011 in a historical context

In March 2011, the Arctic vortex was colder, stronger and more persistent than usual. Figure 1 shows histograms of the polar cap temperature, breakup date of the Arctic vortex, ENSO index, QBO index and North Pacific SST index in the Arctic late winter 2011 with respect to the 1979–2011 period. A histogram of March mean temperatures for the Arctic polar cap at 50 hPa is shown in Figure 1b. The March 2011 temperature of 208.5 K (indicated by the red outline) is more than two standard deviations lower than the climatological mean value (216.8 K) and is the second–lowest value in the 1979–2011 period. The lowest value (206.1 K, indicated by the blue outline) occurred in 1997.

The breakup of the Arctic vortex occurs in late winter. A histogram of breakup dates at 450 K is shown in Figure 1c. The breakup date in 2011 was 19th April in the NCEP–2 reanalysis, later than the mean date of 20th March in the NCEP reanalyses and 10th April in the CPC reanalysis. The breakup date in 2011 was, depending on the zonal wind dataset, either the third or fourth latest of the satellite era. The late breakup of the Arctic vortex is consistent with the low temperatures and total ozone observed in March 2011 (see Figures 1a and 1b).

Unusually cold conditions in the Arctic stratosphere in March 2011 correspond with unusually weak planetary wave driving in February 2011. Newman et al. (2001) found that polar lower stratospheric temperature is correlated with mid–latitude eddy heat flux at 100 hPa, with a 1–2 month lag; this finding suggests that weaker than usual eddy heat flux in February should correspond with a colder than usual Arctic lower stratosphere in March. Figure 2 shows that February eddy heat flux and March polar cap temperature at 50 hPa are indeed well correlated, and highlights the unusually low values observed in 2011.

March temperature anomalies in 2011 and 1997 are shown in Figures 3a and 3b. In both 1997 and 2011, the Arctic stratosphere cooled strongly while the mid–latitudes and Arctic troposphere warmed weakly. Consistent with the temperature differences, zonal winds were relatively stronger at high latitudes; peak wind differences exceeded 20 m s^{-1} at 10 hPa at high latitudes

115   (not shown). The magnitude of the stratospheric cooling was larger in 1997 than in 2011.

116   February eddy heat flux was weaker in 1997 than in 2011 as well (see Figure 2).

117

118   **3.2   Influence of ENSO and the QBO on the Arctic stratosphere in March**

119   La Niña and QBO–westerly conditions persisted through March 2011. The Niño 3.4 index was

120   strongly negative in January through March 2011, indicating La Niña conditions (Figure 1d). In

121   March 2011, equatorial zonal winds at 50 hPa were approximately 6 m s^{-1} (Figure 1e), indicating

122   the westerly phase of the QBO.

123

124   This section compares the temperature anomalies observed in March 2011 with those observed

125   during typical La Niña conditions and during the westerly phase of the QBO. The March

126   temperature response to La Niña events is estimated by comparing years when the Niño 3.4

127   index is equal to or less than −1 (as in 2011) with years when the Niño 3.4 index is between −0.5

128   and 0.5 (i.e., ENSO neutral). Figure 3c shows that, in the Arctic stratosphere, the typical March

129   temperature response to a La Niña event is a weak warming. The La Niña response is

130   inconsistent with the observed temperature response in both 1997 and 2011.

131

132   The QBO was in its westerly phase during the 2010–2011 winter season (Figure 1e). The March

133   temperature response to the phase of the QBO is estimated by comparing composites of QBO–

134   westerly years and QBO–easterly years. The typical March temperature response is a relative

135   warming of the Arctic stratosphere that increases with altitude (Figure 3d). As for the La Niña

136   response, the temperature response to QBO–westerly conditions is inconsistent with the observed

137   temperature response in both 1997 and 2011.

138

139   In summary, the patterns and magnitudes of the March 2011 temperatures differences from

140   climatology are similar to those seen in March 1997, but different from the Arctic response to

141   both La Niña events and to the phase of the QBO. March zonal wind and February eddy heat

142   flux differences are consistent with these conclusions. That is, the weak eddy heat flux in

143   February and low temperatures in March 2011 are not related to either ENSO or the QBO.

144

145   **3.3   Influence of North Pacific SSTs on the Arctic stratosphere in March**

146   This section considers the influence of extra–tropical SSTs on the Arctic stratosphere in March.
147   March lower stratospheric temperature and February planetary wave driving should be most
148   influenced by SST variability in the mid– to late winter.   As noted in Section 3.2,
149   January/February SSTs in the tropical Pacific and March polar cap temperatures are not
150   correlated. However, SSTs in the North Pacific, poleward of 40°N and close to the dateline, are
151   strongly negatively correlated with March polar cap temperatures. This region corresponds with
152   the dominant mode of SST variability in the North Pacific in boreal winter i.e., the 'subarctic
153   mode' identified by Nakamura et al., (1997).   The subarctic mode is associated with SST
154   variability at decadal timescales, caused by variability in the Kuroshio and Oyashio currents, and
155   is not influenced by variability in the tropical Pacific (i.e., variability related to ENSO).
156   Furthermore, the subarctic SST mode is not related to the Pacific Decadal Oscillation (PDO)
157   (index updated from Mantua et al., 1997; Zhang et al., 1997).
158
159   The positive phase of the subarctic SST mode tends to weaken the Aleutian low and thus the
160   Pacific–North American (PNA) circulation pattern. Garfinkel et al. (2010) found that variability
161   of the Aleutian low modulates the strength of the Arctic vortex in mid–winter, with a similar
162   relationship in late winter (not shown).
163
164   In this study, the subarctic SST index is defined as the January/February mean SST anomaly
165   from the 1979–2011 climatology, in the 40–50°N, 160–200°E region. The subarctic SST index
166   was strongly positive in both 1997 and 2011 (Figure 1f). Figure 3e shows the difference
167   between March temperatures in years when the subarctic SST index is strongly positive as
168   compared with years when the index is strongly negative: The Arctic stratosphere is relatively
169   colder (by approximately 6 K at 50 hPa), while below 500 hPa the Arctic is approximately 2 K
170   warmer. The structure and magnitude of these temperature differences are broadly consistent
171   with the March temperature anomalies observed in 1997 and 2011 (Figures 3a and 3b),
172   suggesting that North Pacific SST variability strongly contributed to variability in the Arctic
173   stratosphere in March 1997 and 2011.
174
175   **4   Discussion**

176   Unusual dynamical conditions were observed in the Arctic stratosphere in March 2011.

177   Tropospheric planetary wave driving was unusually weak, consistent with a strong, stable Arctic

178   vortex in late winter and a relatively late vortex breakup. From a zonal mean perspective, the

179   dynamical conditions observed in 2011 were not unprecedented: February eddy heat flux was

180   weaker and March polar cap temperature was lower in 1997 than in 2011.

181

182   Recent cooling of the Arctic lower stratosphere has been reported by e.g., Randel et al. (2009)

183   and Kennedy et al. (2010). In the NCEP–2 reanalysis in March, polar cap temperature at 50 hPa

184   decreased 1.6 ± 1.3 K year^{-1} during the 1979–2011 period. During this period, cooling of the

185   Arctic lower stratosphere can be largely attributed to increased radiative forcing by greenhouse

186   gases and to ozone depletion (Shine et al., 2003; Stolarski et al., 2010). However, this modest

187   linear trend in March does not explain the anomalous conditions in 1997 and 2011, when the

188   Arctic lower stratosphere was more than 10 K below the climatological mean.

189

190   Similarly, the phase of the 11–year solar cycle does not account for the anomalous conditions in

191   March 2011. The solar cycle can be characterized by the solar flux at 2800 MHz

192   (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/Penticton_Observed/mon

193   thly/MONTHLY.OBS); both 1997 and 2011 were within a few years of solar minima. Since the

194   QBO was easterly in 1997 but westerly in 2011, the product of the solar cycle and QBO

195   anomalies had the opposite sign in 1997 as compared with 2011. Though this quantity is well

196   correlated with polar variability (Haigh and Roscoe, 2006), it does not explain the anomalously

197   strong vortex events in both 1997 and 2011.

198

199   ENSO and the QBO do not explain the unusual dynamical conditions in March 2011. While La

200   Niña conditions tend to strengthen the Arctic vortex in mid–winter, the La Niña signal weakens

201   and begins to reverse by March. In Goddard Earth Observing System Chemistry–Climate

202   Model, Version 2 (GEOS V2 CCM) simulations (model formulation as described by Hurwitz et

203   al., 2011), the Arctic lower stratosphere is cooler in March under La Niña and QBO–westerly

204   conditions, as compared with ENSO neutral and QBO–easterly; however; the magnitude of this

205   cooling is an order of magnitude less than observed in March 2011. Furthermore, the structure

206 and magnitude of dynamical anomalies in the Arctic stratosphere were similar in March 1997
207 and March 2011, despite different phases of the QBO.
208
209 Positive SST anomalies in the North Pacific may have contributed to the anomalous conditions
210 in March 2011. Positive SST anomalies in the 40–50°N, 160–200°E region in January and
211 February, such as those observed in 1997 and 2011, are strongly anti–correlated with polar lower
212 stratospheric temperature anomalies in March. Positive SSTs in this region tend to weaken the
213 Aleutian low, leading to a reduced eddy heat flux entering the stratosphere (Garfinkel et al.,
214 2010). The subarctic SST index in January/February and March polar cap temperature at 50 hPa
215 are correlated at the 95% confidence level. However, the relationship between North Pacific
216 SSTs and stratospheric variability is non–linear: While multiple linear regressions to either
217 February eddy heat flux or March polar cap temperature show that the subarctic SST mode is,
218 statistically, the dominant cause of dynamical variability, these linear regressions do not capture
219 the extreme values seen in e.g., 1997 and 2011. A planned modelling study will, by comparing
220 time–slice simulations of the positive and negative extremes of the subarctic SST mode, isolate
221 the impact of North Pacific SSTs on Arctic dynamics and ozone in March.
222

223 **Acknowledgements**

227

227 **References**

228 Finger, F. G., Gelman, M. E., Wild, J. D., Chanin, M. L., Hauchecorne, A., and Miller, A. J.:

229 Evaluation of NMC upper stratospheric temperature analyses using rocketsonde and lidar data,

230 Bull. Am. Meteorol. Soc., 74, 789–799, 1993.

231

232 Garfinkel, C. I., and Hartmann, D. L.: Different ENSO teleconnections and their effects on the

233 stratospheric polar vortex, J. Geophys. Res., 113, D18114, doi:10.1029/2008JD009920, 2008.

234

235 Garfinkel, C. I., Hartmann, D. L., and Sassi, F.: Tropospheric precursors of anomalous Northern

236 Hemisphere stratospheric polar vortices, J. Climate, 23, doi:10.1175/2010JCLI3010.1, 2010.

237

238 Gelman, M. E., Miller, A. J., Johnson, K. W., and Nagatani, R. M.: Detection of long–term

239 trends in global stratospheric temperature from NMC analyses derived from NOAA satellite

240 data, Adv. Space Res., 6(10), 17–26, 1986.

241

242 Haigh, J. D., and Roscoe, H. K.: Solar influences on polar modes of variability, Meteologische

243 Zeitschrift, 15, 371–378, 2006.

244

245 Holton, J. R., and Tan, H.–C.: The Influence of the equatorial quasi–biennial oscillation on the

246 global circulation at 50 mb, J. Geophys. Res., 37, 2200–2208, 1980.

247

248 Hurwitz, M. M., Song, I.–S., Oman, L. D., Newman, P. A., Molod, A. M., Frith, S. M., and

249 Nielsen, J. E.: Response of the Antarctic stratosphere to warm pool El Niño events in the GEOS

250 CCM, Atm. Phys. Chem. Discuss., 11, 9743–9767, 2011.

251

252 Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha,

253 S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo,

254 K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D.: The

255 NCEP/NCAR 40–year reanalysis project, Bull. Amer. Meteor. Soc., 77, 437–471, 1996.

256

257   Kennedy, J., and Parker, D.: Global and regional climate in 2009, Weather, 65 (9), 244–250,

258   2010.

259

260   Kanamitsu, M., Ekisuzaki, W., Woollen, J., Yang, S.–K., Hnilo, J. J., Fiorino, M., and Potter, G.

261   L.: NCEP–DOE AMIP–II reanalysis (R–2), Bull. Amer. Meteor. Soc., 83, 1631–1643, 2002.

262

263   Lu, H., Baldwin, M. P., Gray, L. J., and Jarvis, M. J.: Decadal–scale changes in the effect of the

264   QBO on the northern stratospheric polar vortex, J. Geophys. Res., 113, D10114,

265   doi:10.1029/2007JD009647, 2008.

266

267   Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C.: A Pacific interdecadal

268   climate oscillation with impacts on salmon production, Bull. Amer. Meteor. Soc., 78, 1069–

269   1079, 1997.

270

271   Nagatani, R. M., Miller, A. J., Johnson, K. W., and Gelman, M. E.: An eight–year climatology

272   of meteorological and SBUV ozone data, NOAA Tech. Rep. NWS 40, 125 pp., Natl. Weather

273   Serv., Washington, D. C., 1988.

274

275   Nakamura, H., Lin, G., and Yamagata, T.: Decadal climate variability in the North Pacific

276   during the recent decades, Bull. Amer. Meteorol. Soc., 78, 2215–2225, 1997.

277

278   Nash, E. R., Newman, P. A., Rosenfield, J. E., and Schoeberl, M. R.: An objective

279   determination of the polar vortex using Ertel's potential vorticity, J. Geophys. Res., 101, D6,

280   9471–9478, 1996.

281

282   Randel, W. J., Shine, K. P., Austin, J., Barnett, J., Claud, C., Gillett, N. P., Keckhut, P.,

283   Langematz, U., Lin, R., Long, C., Mears, C., Miller, A., Nash, J., Seidel, D. J., Thompson, D. W.

284   J., Wu, F., Yoden, S.: An update of observed stratospheric temperature trends, J. Geophys. Res.,

285   114, D02107, doi:10.1029/2008JD010421, 2009.

286

287 Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P.,
288 Kent, E. C., and Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night
289 marine air temperature since the late nineteenth century, J. Geophys. Res., 108, 4407,
290 doi:10.1029/2002JD002670, 2003.

291

292 Rex, M., Salawitch, R. J., von der Gathen, P., Harris, N. R. P., Chipperfield, M. P., and
293 Naujokat, B.: Arctic ozone loss and climate change, Geophys. Res. Lett., 31, L04116,
294 doi:10.1029/2003GL018844, 2004.

295

296 Rex, M., Salawitch, R. J., Deckelmann, H., von der Gathen, P., Harris, N. R. P., Chipperfield, M.
297 P., Naujokat, B., Reimer, E., Allaart, M., Andersen, S. B., Bevilacqua, R., Braathen, G. O.,
298 Claude, H., Davies, J., De Backer, H., Dier, H., Dorokhov, Fast, H., Gerding, M., Godin–
299 Beekmann, S., Hoppel, K., Johnson, B., Kyro, E., Litynska, Z., Moore, D., Nakane, H.,
300 Parrondo, M. C., Risley, A. D., Skrivankova, P., Stubi, R., Viatte, P., Yushkov, V., Zerefos, C.:
301 Arctic winter 2005: implications for stratospheric ozone loss and climate change, Geophys. Res.
302 Lett., 33, L23808, doi:10.1029/2006GL026731, 2006.

303

304 Shine, K. P., Bourqui, M. S., Forster, P. M. D., Hare, S. H. E., Langematz, U., Braesicke, P.,
305 Grewe, V., Ponater, M., Schnadt, C., Smiths, C. A., Haigh, J. D., Austin, J., Butchart, N.,
306 Shindell, D. T., Randel, W. J., Nagashima, T., Portmann, R. W., Solomon, S., Seidel, D. J.,
307 Lanzante, J., Klein, S., Ramaswamy, V., Schwarzkopf, M. D.: A comparison of model–
308 simulated trends in stratospheric temperatures, Q. J. Royal. Meteorol. Soc., 129, 590, 1565–
309 1588, 2003.

310

311 SPARC CCMVal: SPARC Report on the Evaluation of Chemistry–Climate Models, V. Eyring,
312 T. G. Shepherd, D. W. Waugh (Eds.), SPARC Report No. 5, WCRP–132, WMO/TD–No. 1526,
313 http://www.atmosp.physics.utoronto.ca/SPARC, 2010.

314

315 Stolarski, R. S., Douglass, A. R., Newman, P. A., Pawson, S., and Schoeberl, M. R.: Relative
316 contribution of greenhouse gases and ozone–depleting substances to temperature trends in the
317 stratosphere: a chemistry–climate model study, J. Climate, 23, 26–42, 2010.

318 Stolarski, R. S., and Frith, S. M.: Search for evidence of trend slow–down in the long–term
319 TOMS/SBUV total ozone data record: the importance of instrument drift uncertainty, Atmos.
320 Chem. Phys., 6, 4057–4065, doi:10.5194/acp–6–4057–2006, 2006.
321
322 Trenberth, K. E.: The definition of El Niño, Bull. Amer. Met. Soc., 78, 2771–2777, 1997.
323
324 World Meteorological Organization (WMO): Scientific assessment of ozone depletion: 2010,
325 Global Ozone Research and Monitoring Project, Rep. No. 52, 516 pp., Geneva, Switzerland,
326 2011.
327
328 Zhang, Y., Wallace, J. M., and Battisti, D. S.: ENSO–like interdecadal variability: 1900–93, J.
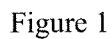329 Climate, 10, 1004–1020, 1997.
330

330 **Figure Captions**

331 Figure 1. Histograms of total ozone and dynamical conditions during the 1979–2011 period: (a)

332 March total ozone averaged between 60–80°N [DU]; (b) March Arctic polar cap temperature at

333 50 hPa [K]; (c) Date of the Arctic vortex breakup at 450 K based on the NCEP–2 (black),

334 NCEP–1 (light gray) and CPC (dark gray) reanalyses, binned into 10–day intervals; (d) January–

335 February–March SST anomaly in the Niño 3.4 region [K]; (e) March zonal winds in the

336 equatorial region at 50 hPa [m s^{-1}]; (f) January/February SST anomaly in the 40–50°N, 160–

337 200°E region [K]. Red (blue) outlines indicate the location of 2011 (1997) conditions. Y–axis

338 values indicate the mid–point of each histogram bin.

339

340 Figure 2. Meridional eddy heat flux at 40–80°N, 100 hPa [K m s^{-1}] in February as a function of

341 Arctic polar cap temperature at 50 hPa [K] in March. Eddy heat flux and temperature values are

342 denoted by year number (e.g., "11" denotes 2011).

343

344 Figure 3. March temperature differences [K] in the NCEP–2 reanalysis: (a) 2011 from the

345 1979–2011 climatological mean; (b) 1997 from the climatological mean; (c) composite of La

346 Niña events from the climatological mean; (d) QBO–westerly as compared with QBO–easterly

347 years. (e) March temperature differences for years when SSTs in the 40–50°N, 160–200°E

348 region are more (less) than one standard deviation greater (less than) the climatological mean. In

349 (c), (d) and (e) black Xs denote differences significant at the 95% confidence level. Zero

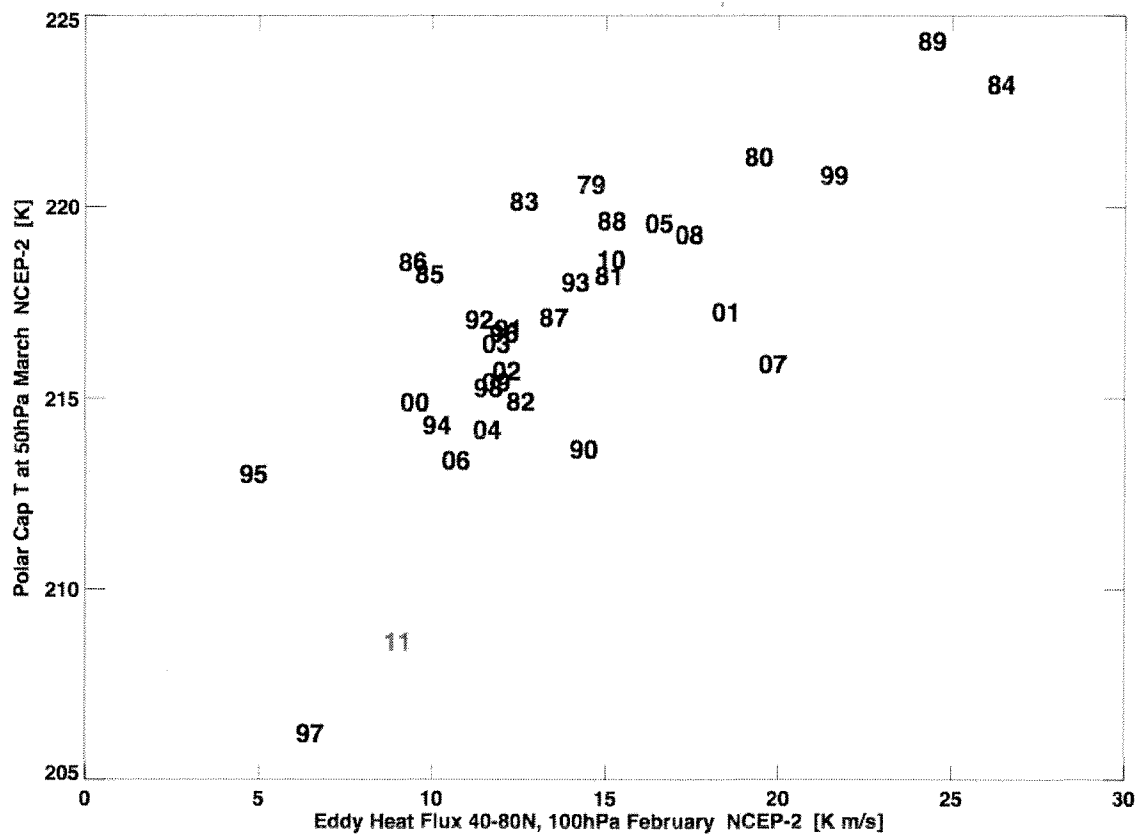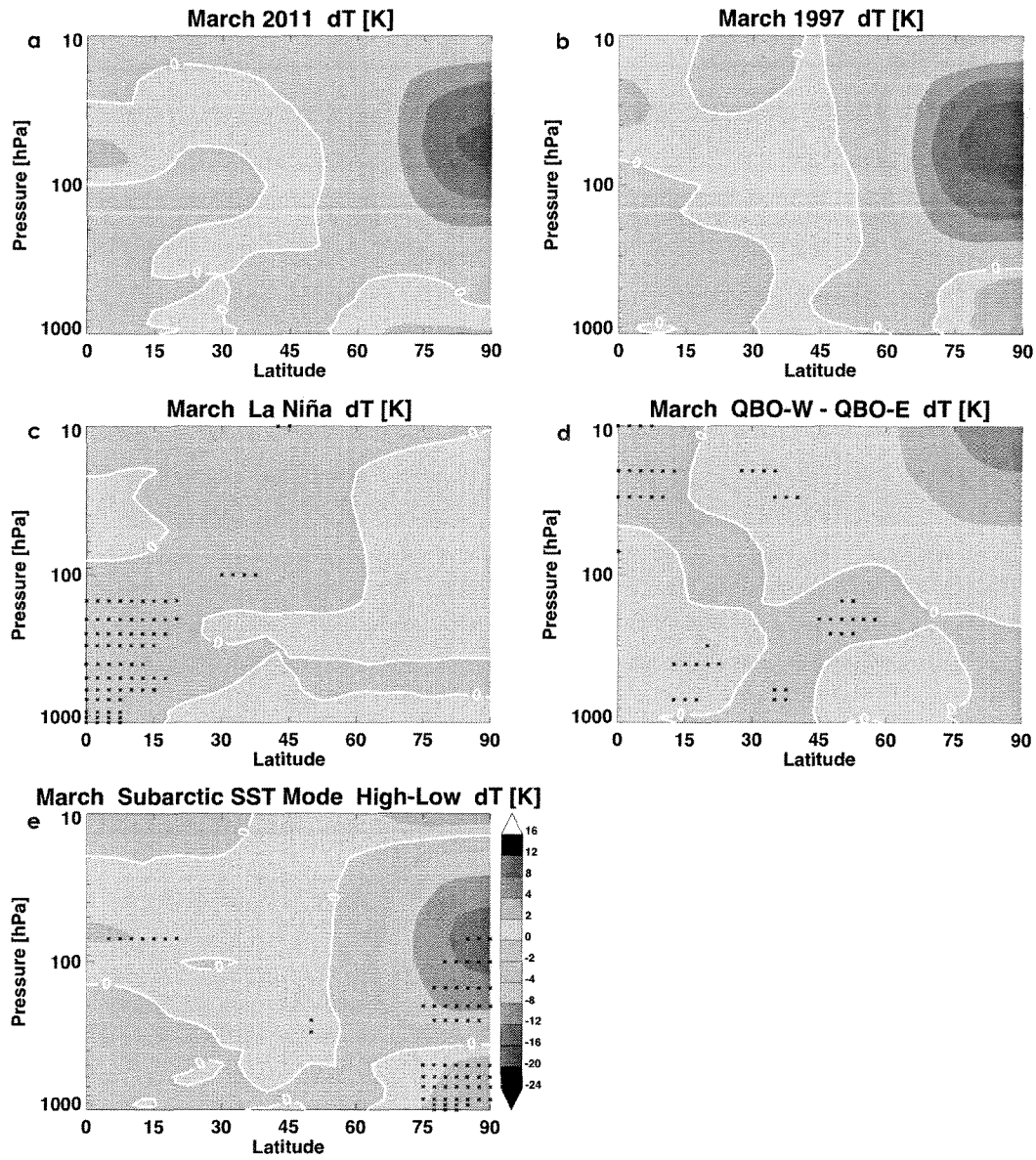350 difference contours are shown in white.

351

Figures

(a) March Total Ozone, 60-80N TOMS/SBUV [DU]

(b) March Polar Cap Temperature at 50 hPa NCEP-2 [K]

(c) Arctic Vortex Breakup Date at 450 K

(d) JFM Nino 3.4 Anomaly [K]

(e) March QBO Index at 50 hPa CPC [m/s]

(f) January/February North Pacific SST Index [K]

352

353   Figure 1

354

354

355   Figure 2

356

356

357   Figure 3