TRANS-ANDEAN PASSAGE OF MIGRATING ARCTIC TERNS OVER PATAGONIA

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SUMMARY

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We assessed migration routes of Arctic Terns *Sterna paradisaea* breeding in Prince William Sound, Alaska, by deploying geolocator tags on 20 individuals in June 2007, recovering six upon their return in 2008 and 2009. The terns migrated south along the North and South American coastlines. As they neared the southern end of the Humboldt Current upwelling off Chile, they stopped their over-water migration and turned eastward, crossing the Andes to reach rich foraging areas in the South Atlantic Ocean off the coast of Argentina. Challenging sea and weather conditions, rather than paucity of food, likely deterred further movement south along the Chilean coast.

Key words: Alaska, Arctic Tern, Andes, Argentina, Chile, geolocation, Humboldt Current, migration, Patagonia, *Sterna paradisaea*

INTRODUCTION

Arctic Terns *Sterna paradisaea* have the longest known migration of any bird species, from the Arctic to the Antarctic, covering up to 80 000 km during a round trip (Egevang *et al.* 2010). We report here on an apparent trans-Andean passage by southward migrating Arctic Terns on a route that takes them from the rich inshore upwellings of southwestern South America, over the Andes, to the highly productive offshore waters of Argentinian Patagonia. We then explore possible reasons for this behavior.

METHODS

Using box traps placed over nests, we captured 20 breeding Arctic Terns at a small colony of approximately 80 individuals in Prince William Sound, Alaska (61°00′N, 148°20′W), during June 2007. We placed activated 1.5 g MK 14 combined geolocators and salt water immersion sensors (British Antarctic Survey) on Darvic leg bands. The combined mass of device and band was less than <3% of body mass, well within acceptable mass limits for devices attached to seabirds (Phillips *et al.* 2003). In 2008 and 2009, we recovered six birds, five of which provided evidence of Andean crossings. Other data from the migration will be presented separately (McKnight *et al.* in press).

We used specialized software developed by the British Antarctic Survey (BAS) to decompress and edit the light data as well as to translate the data into geographic positions. To accomplish these tasks, we defined sunrise and sunset as the times when light levels reached 10 units on the BAS scale of 0 to 64. We chose this light level to represent a sun elevation of 4.75° below the horizon. Next, we used several filters to ensure that only the most reliable positions would be used for analysis. We did not calculate positions for any day or night when shading events rendered sunrise and sunset times uncertain. Because the mountainous terrain may have obstructed the tags' view of the horizon and displaced positions calculated during the crossing, we defined the crossing distance as the distance between the last Pacific point and the first Atlantic point, ignoring intermediate points occurring on land. We excluded all data from within 10 d of an equinox, as equal day length across latitudes at this time precludes latitudinal determination from day length alone. Later, we examined data from dates within 20 d of the equinox and discarded additional points exhibiting obvious latitudinal error. We identified these as positions requiring flight speeds of > 65 km · h^{-1} sustained over a 24 h period, 60% faster than the 40.7 km · h^{-1} over ground reported by Gudmundsson *et al.* (1992). Finally, we smoothed each set of positions twice using the moving average technique (n = 2). To examine individual bird tracks, we used ArcMap 9.1 (ESRI) to generate maps to show smoothed travel paths.

Next, we examined the distances traveled by each bird as well as each bird's apparent velocity. We used data from salt water immersion devices from all five birds to determine the time elapsed between each bird's departure from Pacific waters and subsequent arrival in Atlantic waters. We used trigonometric cosines to calculate the distance traveled between the last recorded Pacific position and the first recorded Atlantic position for each bird. Fixes can be determined only for midnight and noon on any given date; the period of time represented by each calculated distance therefore does not exactly match the corresponding time duration calculated using the salt water immersion data.

We used two methods to examine the conditions under which the birds would have migrated at sea, one at the weather scale of weeks to months and the other at the climate, decadal-century scale. For actual weather conditions, we examined wind speeds between 23 September and 6 November 2007 (a date range that includes all of the tagged birds' South American crossing dates) using QuikScat wind data, produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team (www.remss.com).

We recorded the percentage of gale force inshore winds >63 km · h^{-1}, almost 60% higher than tern migration speeds, at 45°S, 50°S and 55°S (see above).

To smooth inter-annual differences that might obscure climatic factors favoring eastward versus southward movement of terns upon arrival in Patagonian waters, we used the only available time series of data, spanning 1854–1969, from the *US Navy Marine Climatic Atlas of the World* (1979). We examined the monthly percent of wave heights >2 m, mean wind speed, independent of direction, as well as the percentage of head (southeast and south) and tail (northwest and west) winds from August to January at four locations along the Chilean coast (Atlas site 22 at 25°S off Taltal, site 28 at 35°S off Valparaiso, site 33 at 45°S off Isla Chiloé, and site 37 at 55°S off Magallanes).

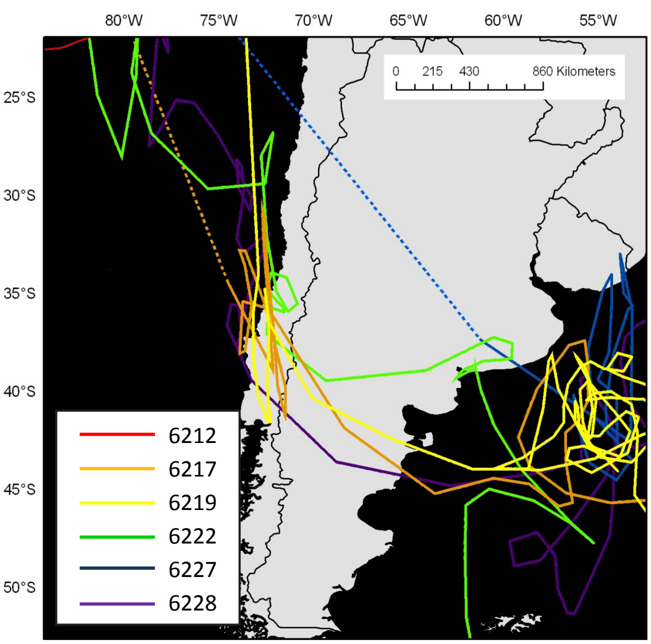

Fig. 1. Tracks of tagged Arctic Terns that crossed the Andes. Dotted line segments indicate missing data resulting from the removal of suspect fixes occurring around the autumnal equinox.

RESULTS

One of the six birds stayed offshore, proceeding south in the Pacific to approximately 60°S, 111°W. The remaining five crossed overland to reach the southern Atlantic Ocean between 1 October and 6 November 2007 (Table 1). The crossing on 1 October did not provide reliable location data, as it occurred within 10 days of the autumnal equinox and showed clear equinox error. The remaining four birds transited between the latitudes of 36°S and 40°S on the Pacific side and 38°S and 46°S on the Atlantic side (Fig. 1). The birds traveled 927–1 286 km between the two oceans at estimated velocities ranging from 34 to 80 km · h^{-1} (Table 1). The salt water immersion data revealed that passage duration ranged from 14.3 h to 35.5 h, but the five durations were grouped into three averaging 15.3 h and two averaging 35 h (Table 1).

Using wind speed data collected contemporaneously in 2007, birds choosing to "round the Horn" or the Straits of Magellan would have experienced a strong probability of high winds (Table 2). Using data collected at the decadal-century scale, mean wind speed doubled between northern Chile and Cape Horn in four of six months (Table 3).

Similarly, the percentage of waves >2 m in height at this scale increased with latitude (Table 4). Interestingly, headwinds coming from the southeast and south predominated north of 35°S, while at 45°S and 55°S, tail winds from the northwest and north predominated (Table 5). Terns forage as they migrate, and tail winds might decrease opportunities to locate prey because their speed would be too rapid over the sea surface (Spear & Ainley 1997).

DISCUSSION

These data raise two questions: (1) how and (2) why do Arctic Terns make the passage from the Pacific to Atlantic oceans across the Andes, rather than continuing to fly south along the Pacific coast? Franklin's Gulls *Leucocephalus pipixcan* may well do the same (Maftei 2013).

In terms of flight performance, both altitude and distance may present challenges for Arctic Terns. Between 36°S and 45°S in Chile and Argentina, terns would have to pass over the Andean Cordillera, where peaks range up to 3 000 m in elevation, although passes are only 1 500–2 000 m. However, Arctic Terns have been reported at altitudes of 500–1 500 m over the Antarctic Peninsula

TABLE 1
Time, distance and velocity data for Arctic Terns crossing the Andes

Bird	Start date	Start time (local Chile)	End date	End time (local Chile)	Start coordinates	End coordinates	Distance (km)[a]	Elapsed time (h)	Required velocity (km · h^{-1})
6227	10/1/2007	18:57	10/3/2007	5:27	ND	ND	ND	35.5	ND
6219	10/9/2007	18:54	10/11/2007	6:24	36.5°S, 72.4°W	44.0°S, 61.6°W	1 237.58	35.7	34.7
6217	10/12/2007	18:12	10/13/2007	10:12	35.8°S, 72.4°W	45.2°S, 63.6°W	1 285.86	16.2	79.4
6228	10/17/2007	19:19	10/18/2007	9:59	39.4°S, 73.3°W	44.9°S, 62.7°W	1 054.12	14.8	71.2
6222	11/5/2007	19:11	11/6/2007	11:31	37.1°S, 72.5°W	38.9°S, 62.2°W	926.98	16.5	56.2

[a] Any mid-crossing coordinates were excluded from distance calculations because of the tendency for land-based points to be displaced southward in response to horizon obstruction by mountains.

(Gudmundsson *et al.* 1992) and 1 000–3 000 m over Scandinavia (Alerstam 1985), so the altitudinal challenge presented by the Andes lies well within Arctic Tern flight capabilities. The velocities required to cover the distances involved are above the reported range for Arctic Terns (Gudmundsson *et al.* 1992; Spear & Ainley 1997a); however, average Patagonian winds from the west can exceed 30 km · h^{-1} at 50 m above ground (Nierenberg *et al.* 1999), producing a speed over ground that would bring a trans-Andean crossing well within the flight capability of Arctic Terns in less than two days, obviating the need to feed during passage.

There are two probable reasons that Arctic Terns did not continue south: food and weather. The terns turned east and inland between 36°S and 40°S. The Chilean coast at 40°S is the southern limit of the highly productive Humboldt Current system (Tarazona & Arntz 2001, Acha *et al.* 2004); terns proceeding farther south would face declining food availability. Recent work indicates, however, that suitable food may exist to the south. The anchoveta *Engraulis ringens*, the major pelagic prey species of the Humboldt upwelling (Schaefer 1967), appears to have extended its range and now spawns south to 47°S in coastal fjords (Bustos *et al.* 2008). In addition, the Fuegian sprat *Sprattus fuegensis* supports a small artisanal fishery south of 41°S in the interior waters of the Chiloé Archipelago (Aranis *et al.* 2007). Acoustic surveys indicate that *Sprattus* is the most common schooling fish in the area, especially in fjords and channels of interior Chilean waters (Niklitschek *et al.* 2008). For terns continuing farther south and through the Beagle Channel or Straits of Magellan, the presence of these small, near-surface schooling fish could provide opportunities for foraging at certain times of year.

TABLE 2
Frequency of gale force winds > 63 km · h^{-1} at 45°S, 50°S and 55°S along the west coast of Chile during the study period, based on QuikScat data

Month	Frequency, number of gales per month	Latitude		
		45°S	50°S	55°S
September	8	0	3	7
October	31	5	9	16
November	5	0	0	2
Total	44	5	12	25
% of all gales		11	27	57

TABLE 3
Mean wind speeds by month at different latitudes between 25°S and 55°S, 1854–1969

Latitude	Month; wind speed (km · h^{-1})					
	Aug	Sept	Oct	Nov	Dec	Jan
25°S	25	23.1	20.4	21.5	19.6	32.2
35°S	26.7	25.4	23	23.15	23.3	27
45°S	36.1	29.8	28.3	28.7	27.8	24.1
55°S	42	46.5	45.2	42.6	35	40.7

Source: US Navy Marine Climatic Atlas of the World, South Pacific Ocean, 1979

In contrast, for birds migrating across land, Patagonia appears to provide poor freshwater resources. In Argentinian Patagonia, Darwin (1845: April 22, 1834) noted "The curse of sterility is on the land, and the water flowing over a bed of pebbles partakes of the same curse." During the austral spring, runoff from Andean snow and glaciers leads to flooding of Chilean rivers, which would decrease access to prey (Habit *et al.* 2005, Pascual *et al.* 2005).

In contrast to the apparently poor forage availability along the terrestrial portion of the route, off the Argentinian coast there is enhanced marine productivity from frontal boundaries between mixed and stratified waters inshore and between the Brazil and Malvinas/Falkland currents farther offshore (Olson *et al.* 1988, McKnight *et al.* 2013), resulting in major foraging aggregations of seabirds (Cooke & Mills 1972, Boersma & Rebstock 2009). A non-stop transit from the Pacific to the Atlantic, like the southern passage, appears to offer ample opportunities for foraging at its eastern terminus.

Weather may be a factor leading Arctic Terns to bypass the waters of southern Chile and Argentina. The increased likelihood of encountering heavy winds may deter terns from taking the southern route. Both average wind speed as well as gale frequency increase

TABLE 4
Percentage of wave heights >2 m by latitude during 1854–1969

Location	Month; % of wave heights >2 m					
	Aug	Sept	Oct	Nov	Dec	Jan
25°S	50	53	46	38	38	40
35°S	53	29	38	71	43	40
45°S	63	75	64	57	64	49
55°S	91	ND	ND	89	50	73

Source: US Navy Marine Climatic Atlas of the World, South Pacific Ocean, 1979
ND = not determined.

TABLE 5
Directions of winds at different latitudes, August–January during 1854–1969 between 25°S and 55°S. Southeast and south winds would be head winds, and northwest and north winds would be tail winds for southerly migrating Arctic Terns

Location		Month; % of winds					
		Aug	Sept	Oct	Nov	Dec	Jan
25°S	SE + S	70	80	78	85	82	71
	NW + N	9	6	6	3	4	6
35°S	SE + S	27	40	36	48	50	62
	NW + N	35	31	34	29	25	16
45°S	SE + S	15	15	20	17	16	18
	NW + N	47	46	47	56	51	46
55°S	SE + S	12	11	4	10	9	6
	NW + N	50	57	61	48	57	66

Source: US Navy Marine Climatic Atlas of the World, South Pacific Ocean, 1979 considerably with latitude south of 36°–39°S. The average winds at 55°S from August to January are 42 km · h^{-1} (Table 4), slightly faster than the 40.7–43.56 km · h^{-1} Arctic Tern flight speeds reported by Gudmundsson *et al.* (1992) and Spear & Ainley (1997b). Gales (winds >63 km · h^{-1}) exceed this by almost 60% and are present 27% of the time at 50°S and 57% of the time at 55°S. Such conditions appear likely to severely impair flight performance in the Arctic Tern.

Additionally, birds taking the southern route might face reduced foraging opportunities, even if prey were abundant in the waters of southern Chile and Argentina. Increased wave heights can reduce the depth at which terns *Sterna* spp. track their prey in the water column (Taylor 1983). Although light winds may aid terns in prey capture (e.g. Dunn 1973, Stienen *et al.* 2000), wind speeds above 25–33 km · h^{-1} greatly diminish foraging success (e.g. Boecker 1967, Salt & Willard 1971, Taylor 1983). Foraging in heavy winds may also result in increased metabolic costs, another important consideration for long-distance migrants that may already be functioning near their energetic limits (e.g. Gabrielson *et al.* 1987).

Given the twin challenges of demanding flight and foraging conditions represented by the "water" route to their wintering grounds around the Antarctic Peninsula, migrating terns might increase survival by crossing east over the Andes, avoiding the turbulent marine conditions of southern Chile and Argentina. Although we have examined only a small part of the southward migration of Pacific Arctic Terns, their unanticipated use of the trans-Andean passage illustrates the complex interplay of factors that can shape the evolution of migratory routes of seabirds.

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REFERENCES

ACHA, E.M., MIANZAN, H.W., GUERRERO, R.A., FAVERO, M. & BAVA, J. 2004. Marine fronts at the continental shelves of austral South America. *Journal of Marine Systems* 44: 83–105.

ALERSTAM, T. 1985. Strategies of migratory flight, illustrated by Arctic and common terns, *Sterna paradisaea* and *Sterna hirundo*. Migration: mechanisms and adaptive significance. *Contributions in Marine Science Supplement* 27: 580–603.

ARANIS, R., MELÉNDEZ, C.A.R., PEQUEÑO R.G., & CERNA T.F. 2007. *Sprattus fuegensis* en aguas interiores de Chiloe, Chile. (Osterchthyes: Clupeiformes: Clupeidae). *Gayana* 71: 102–113.

BOECKER, M. 1967. Vergleichende Untersuchungen zur Nahrungs und Nistökologie der Flußseeschwalbe (*Sterna hirundo* L.) und der Küstenseeschwalbe (*Sterna paradisaea* Pont.). *Bonner Zoologische Beiträge* 18: 15–126.

BOERSMA, P.D. & REBSTOCK, G.A. 2009. Foraging distance affects reproductive success in Magellanic penguins. *Marine Ecology Progress Series* 375: 263–275.

BUSTOS, C.A., LANDAETA, M.F., & BALBONTÍN, F. 2008. Spawning and early nursery areas of anchoveta *Engraulis ringens* Jenyns, 1842 in fjords of southern Chile. *Revista de Biología Marina y Oceanografía* 43: 381–389.

COOKE, F. & MILLS, E.L. 1972. Summer distribution of pelagic birds off the coast of Argentina. *Ibis* 114: 245–251.

DARWIN, C. 1845. April 22, 1834. *Journal of Researches into the Natural History and Geology of the Countries Visited during the Voyage of H.M.S. Beagle round the World, under the Command of Capt. Fitz Roy, R.N.* (Second ed.). London: John Murray.

DUNN, E.K. 1973. Changes in fishing ability of terns associated with windspeed and sea surface conditions. *Nature* 244: 520–521.

EGEVANG, C., STENHOUSE, I.J., PHILLIPS, R.A., PETERSEN, A., FOX, J.W. & SILK, J.R.D. 2010. Tracking of Arctic Terns *Sterna paradisaea* reveals longest animal migration. *Proceedings of the National Academy of Sciences* 107: 2078–2081.

GABRIELSON, G.W., MEHLUM, F. &. NAGY, K.A. 1987. Daily energy expenditure and energy utilization of free-ranging Black-legged Kittiwakes. *Condor* 89: 126–132.

GUDMUNDSSON, G.A., ALERSTAM, T. & LARSSON, B. 1992. Radar observations of northbound migration of the Arctic tern, *Sterna paradisaea*, at the Antarctic Peninsula. *Antarctic Science* 4: 163–170.

HABIT, E., BELK, M.C., TUCKFIELD, R.C. & PARRA, O. 2005. Response of the fish community to human-induced changes in the Bíobío River in Chile. *Freshwater Biology* 51: 1–11.

MAFTEI, M. 2013. First record of Franklin's Gull from Antarctica. *Marine Ornithology* 41: 149–150.

McKNIGHT, A., ALLYN, A.J., DUFFY, D.C. & IRONS, D.B. In press. "Stepping stone" pattern in migrating Arctic Terns reveals the importance of upwelling areas. *Marine Ecology Progress Series* 491: 253–264.

NIERENBERG, R.D., LABRAGA, J.C. & FRUMENTO, A. 1999. Wind resource mapping of Patagonia, Argentina. American Wind Energy Association, June, 1999. http://ron-nierenberg.com/dowloads/Wind_Resource_Mapping_of_Patagonia_Argentina.pdf

NIKLITSCHEK, E., TOLEDO, P., HERNÁNDEZ, E., NELSON, J., SOULE, M., HERRANZ, C., MURILLO, C. & VALENZUELA, X. 2008. *Identificación y evaluacion hidroacustica de pequeños pelágicos en aguas interiores de la X y XI Regiones, año 2007.* Informe CT 2009–004. Coyhaique, Chile: Universidad Austral de Chile.

OLSON, D.B., PODESTA, G.P., EVANS R.H. & BROWN, O.B. 1988. Temporal variations in the separation of Brazil and Malvinas Currents. *Deep-Sea Research* 35: 1971–1990.

PASCUAL, M.A., CUSSAC, V., DYER, B., SOTO, D., VIGLIANO, P., ORTUBAY, S. & MACCHI, P. 2007. Freshwater fishes of Patagonia in the 21st century after a hundred years of human settlement, species introductions, and environmental change. *Aquatic Ecosystem Health Management* 10: 212–227.

PHILLIPS, R.A., XAVIER, J.C. & CROXALL, J.P. 2003. Effects of satellite transmitters on albatrosses and petrels. *Auk* 120: 1082–1090.

PHILLLIPS, R.A., SILK, J.R.D., CROXALL, J.P., AFANASYEV, V. & BRIGGS, D.R. 2004. Accuracy of geolocation estimates for flying seabirds. *Marine Ecology Progress Series* 266: 265–272.

SALT, G.W. & WILLARD, D.E. 1971. The hunting behavior and success of Forster's Tern. *Ecology* 52: 989–998.

SCHAEFER, M.B. 1967. Dynamics of the fishery for the anchoveta *Engraulis ringens* off Peru. *Botletin del Instituto del Mar de Peru—Callao* 1: 189–304.

SPEAR, L.B. & AINLEY, D.G. 1997a. Flight behavior of seabirds in relation to wind direction and wing morphology. *Ibis* 139: 221–233.

SPEAR, L.B. & AINLEY, D.G. 1997b. Flight speed of seabirds in relation to wind speed and direction. *Ibis* 139: 234–251.

STIENEN, E.W.M., VAN BEERS, P.W.M., BRENNINKMEIJER, A., HABRAKEN, J.M.P.M., RAAIJMAKERS, M.H.J.E. & VAN TIENEN, P.G.M. 2000. Reflections of a specialist: patterns in food provisioning and foraging conditions in Sandwich Terns *Sterna sandvicensis. Ardea* 88: 33–49.

TARAZONA, J. & ARNTZ, W. 2001. The Peruvian coastal upwelling system. In: Seeliger, U. & Kjerfve, B. (Eds.). *Coastal Marine Ecosystems of Latin America. Ecological Studies,* vol. 144. Berlin: Springer. pp. 229–244.

TAYLOR, I.R. 1983. Effect of wind on the foraging behaviour of Common and Sandwich Terns. *Ornis Scandinavica* 14: 90–96.

US Navy Marine Climatic Atlas of the World (South Pacific Ocean, volume 5). 1979. NAVAIR 50-1C-532. Washington, D.C.: National Climatic Data Center, NESDIS, NOAA, US Department of Commerce.

WILSON R.P., DUCAMP, J.J., REES, W.G., CULIK B.M. & NICKAMP, K. 1992. Estimation of location: global coverage using light intensity. In: Priede, I.G. and Swift, S.M. (Eds.). *Wildlife telemetry: remote monitoring and tracking of animals.* New York: Ellis Horwood. pp. 131–134.